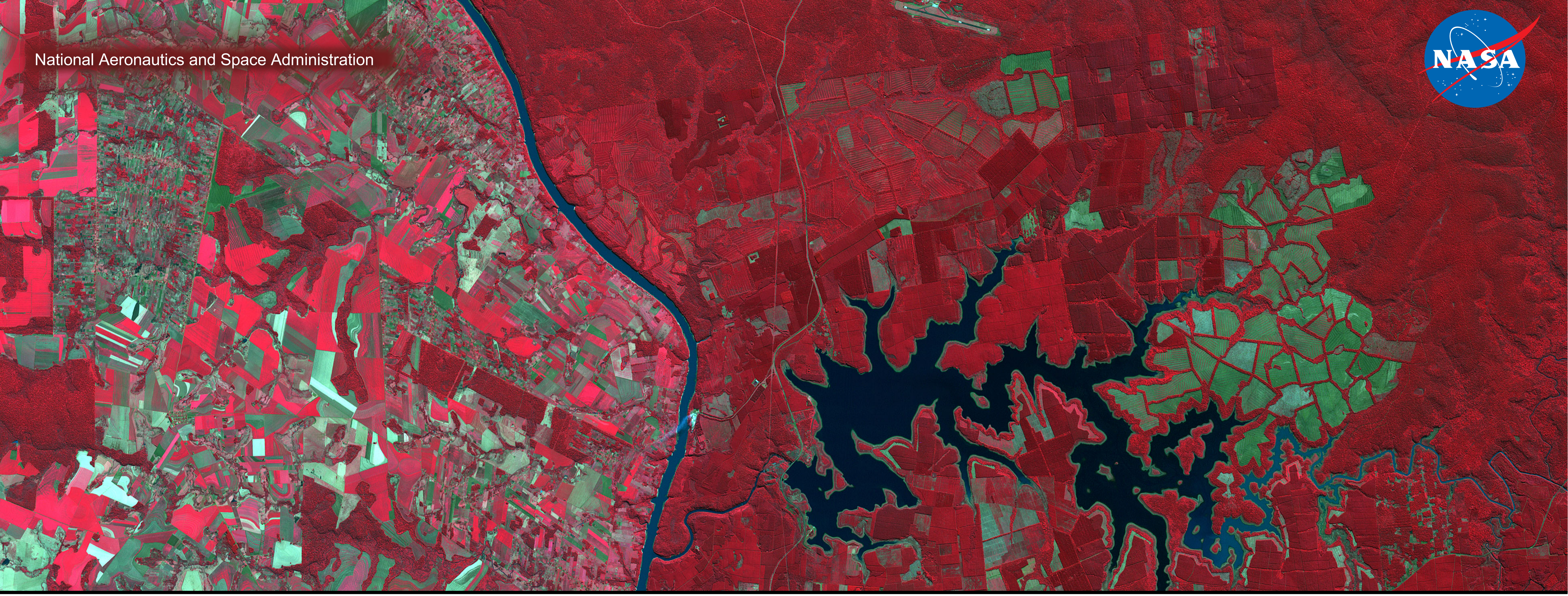


Basics of Synthetic Aperture Radar (SAR)

Erika Podest

29 November 2017

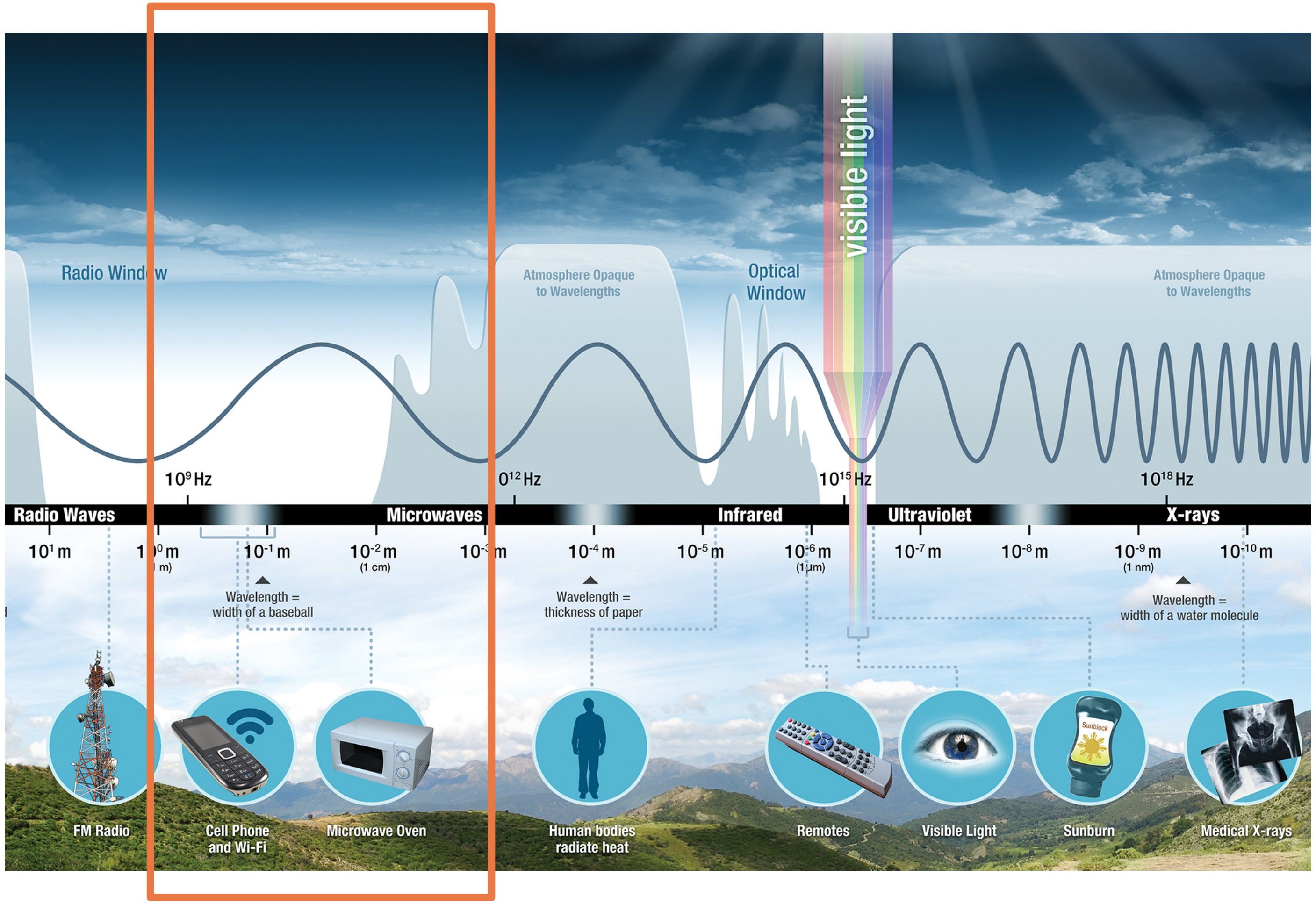
Learning Objectives

By the end of this presentation, you will be able to:

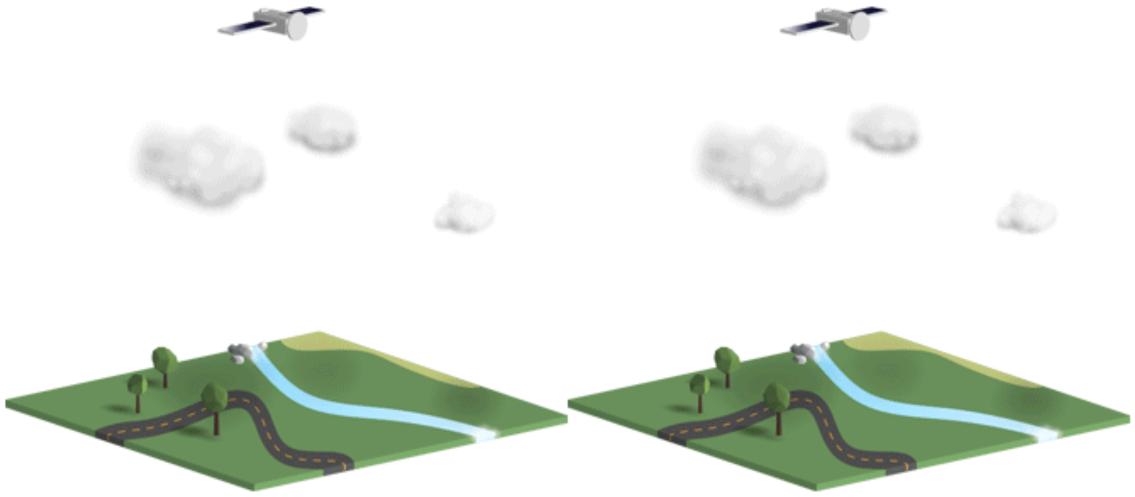
- Understand the physics of SAR image formation
- Describe the interaction of SAR with the land surface
- Describe the necessary data preprocessing
- Understand the information content in SAR images

The Electromagnetic Spectrum

- Optical sensors measure reflected solar light and only function in the daytime
- The surface of the Earth cannot be imaged with visible or infrared sensors when there are clouds
- Microwaves can penetrate through clouds and vegetation (depending on frequency), and can operate in day or night conditions



Active and Passive Remote Sensing



Passive | Sensors detect only what is emitted from the landscape, or reflected from another source (e.g., light reflected from the sun).

Active | Instruments emit their own signal and the sensor measures what is reflected back. Sonar and radar are examples of active sensors.

Passive Sensors:

- The source of radiant energy arises from natural sources
- e.g. the sun, Earth, other "hot" bodies

Active Sensors

- Provide their own artificial radiant energy source for illumination
- e.g. radar, synthetic aperture radar (SAR), LIDAR

Advantages & Disadvantages of Radar Remote Sensing Over Optical

Advantages

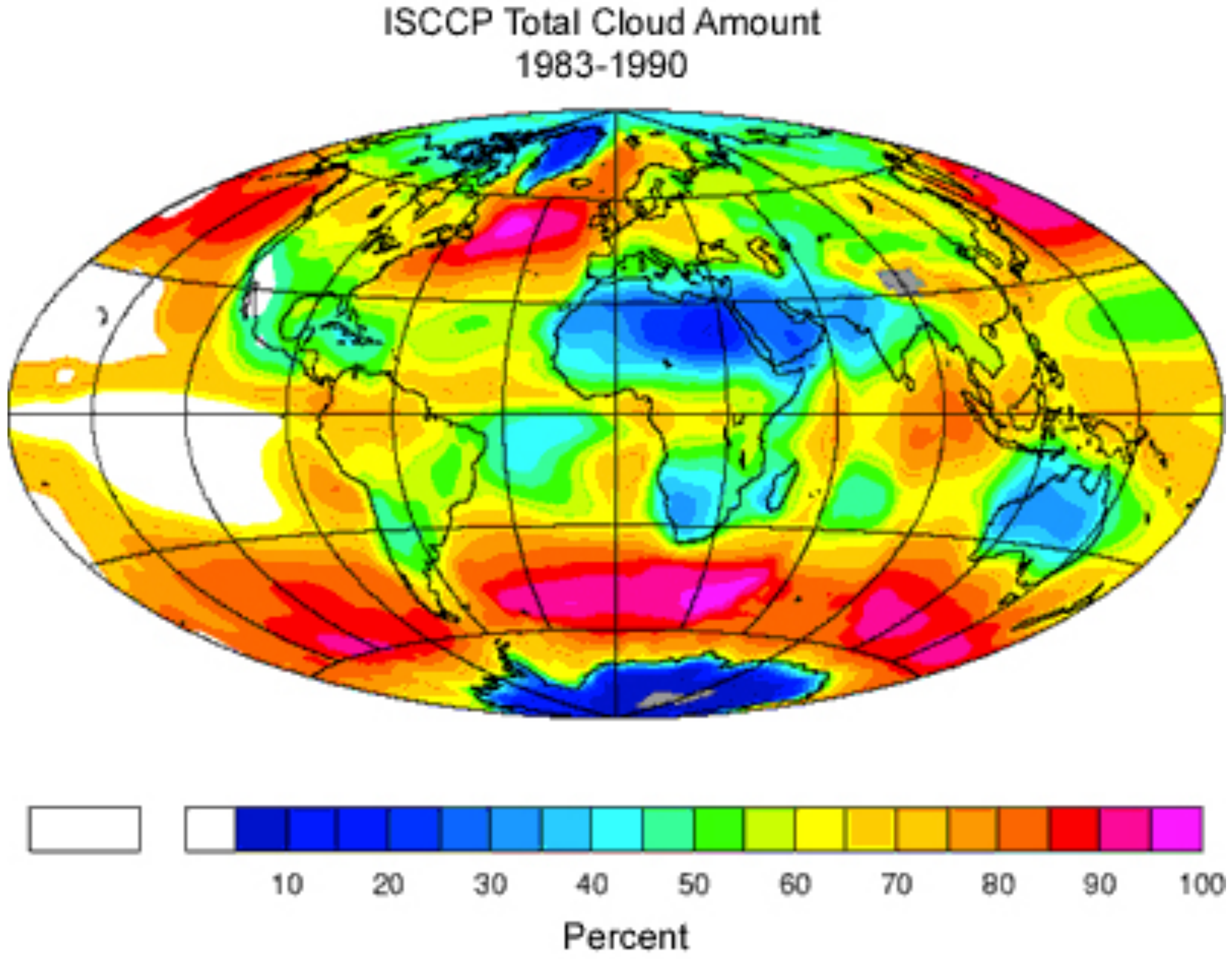
- Nearly all weather capability
- Day or night capability
- Penetration through the vegetation canopy (to a certain degree)
- Penetration through the soil (to a certain degree)
- Minimal atmospheric effects
- Sensitivity to dielectric properties (liquid vs. frozen water)
- Sensitivity to structure

Disadvantages

- Information content is different than optical and sometimes difficult to interpret
- Speckle effects (graininess in the image)
- Effects of topography

Global Cloud Coverage

- Total annual fractional cloud cover averaged from 1983-1990. Compiled using data from the International Satellite Cloud Climatology Project (ISCCP).



Source: ISCCP, NASA Earth Observatory

Optical vs. Radar

Volcano in Kamchatka, Russia, Oct 5, 1994

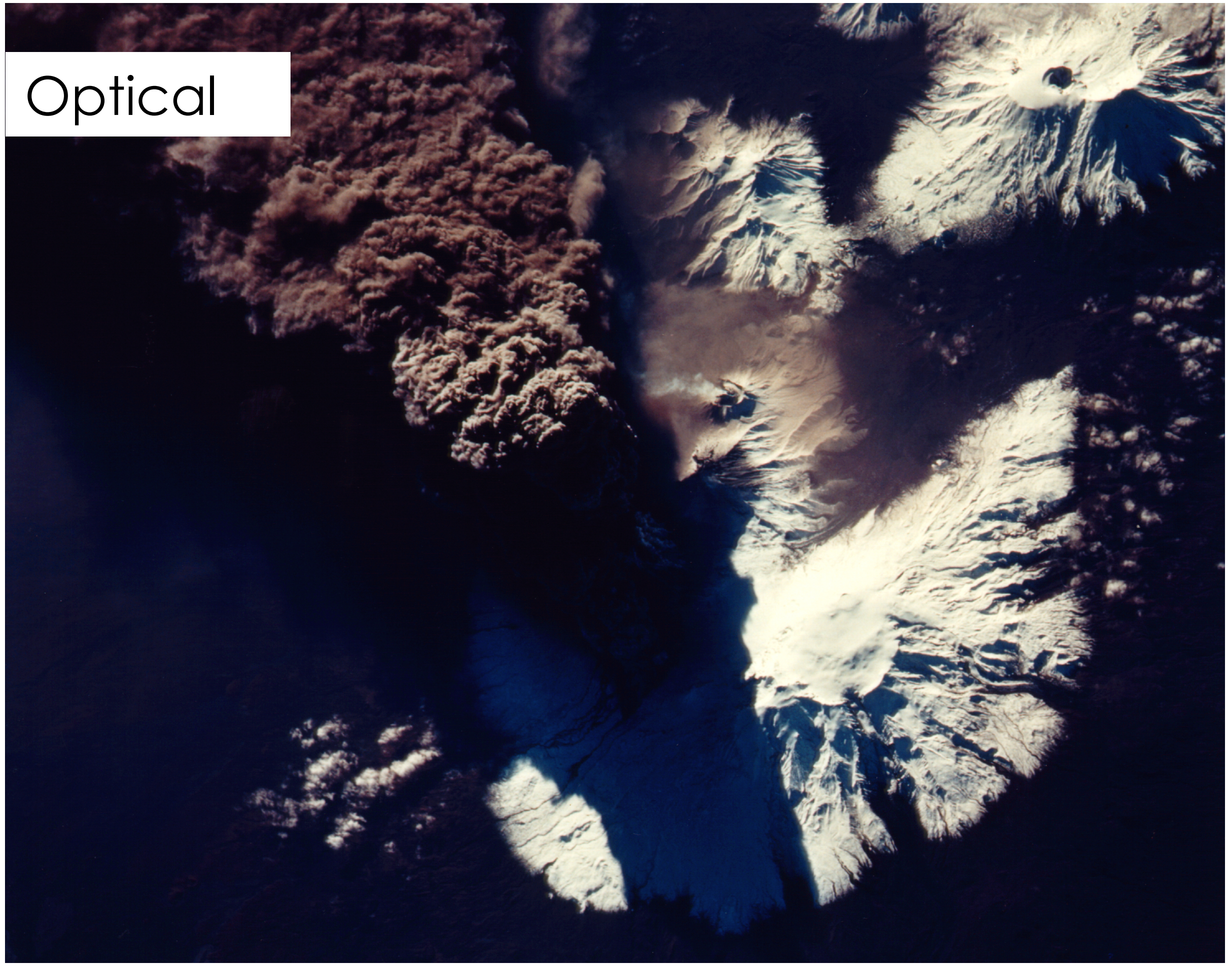
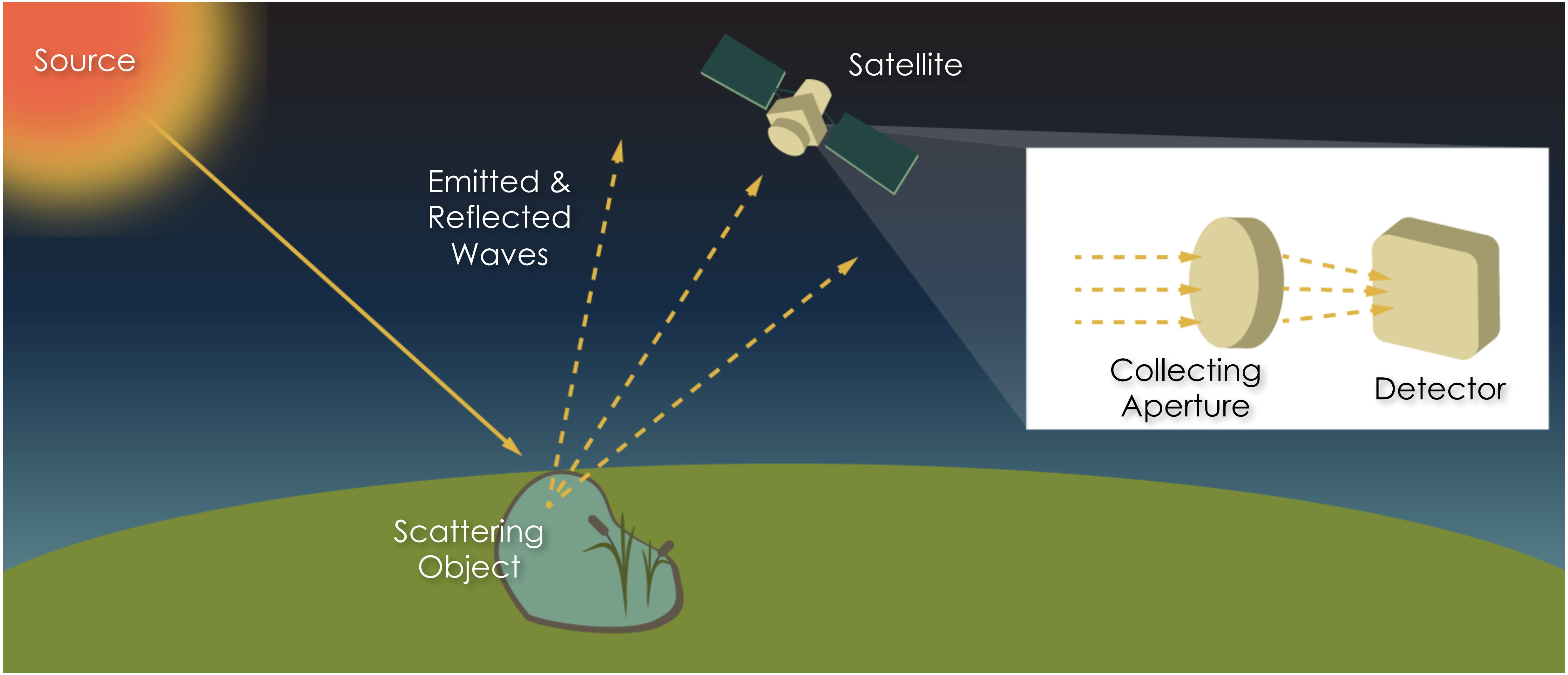


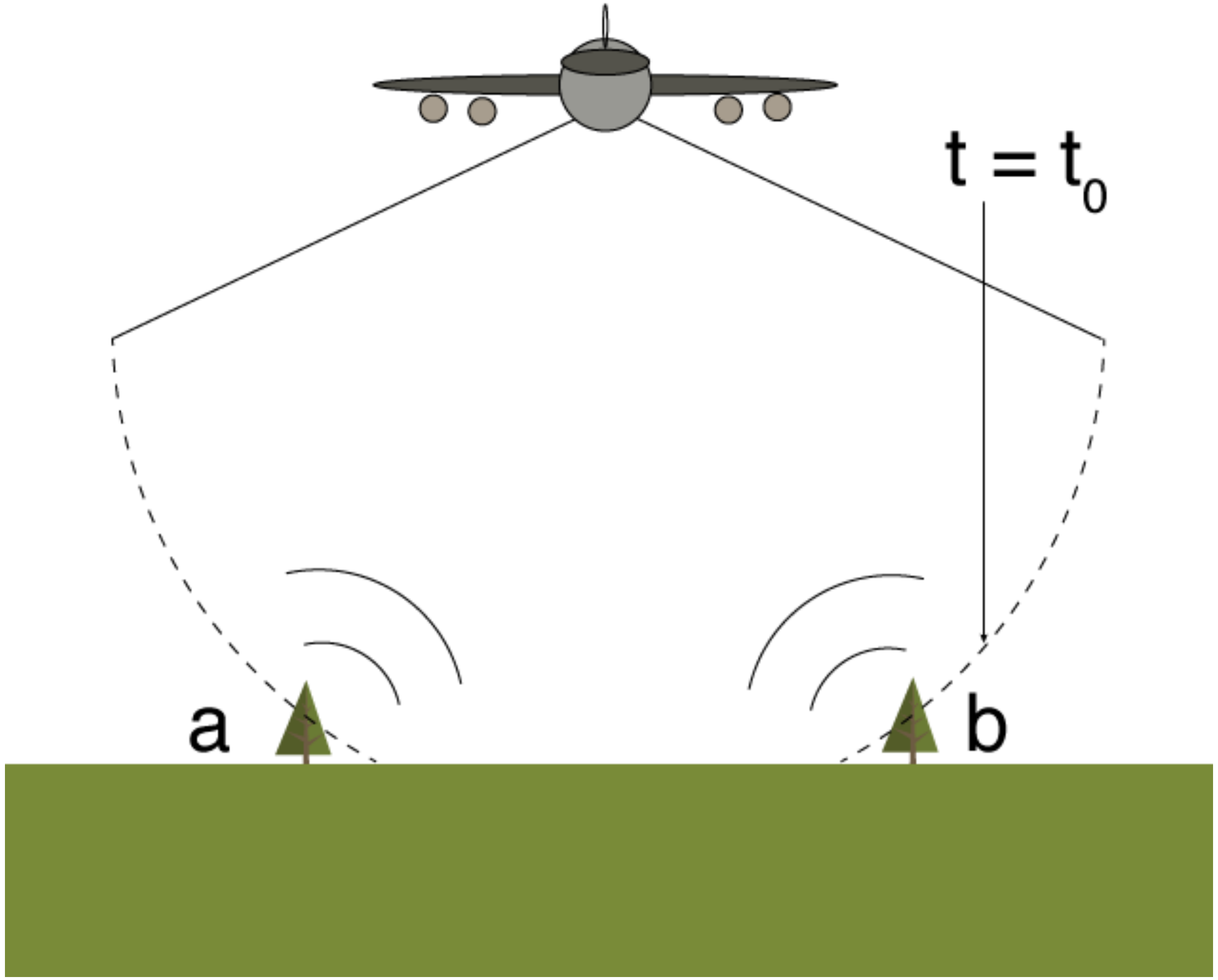
Image Credit: JPL/NASA

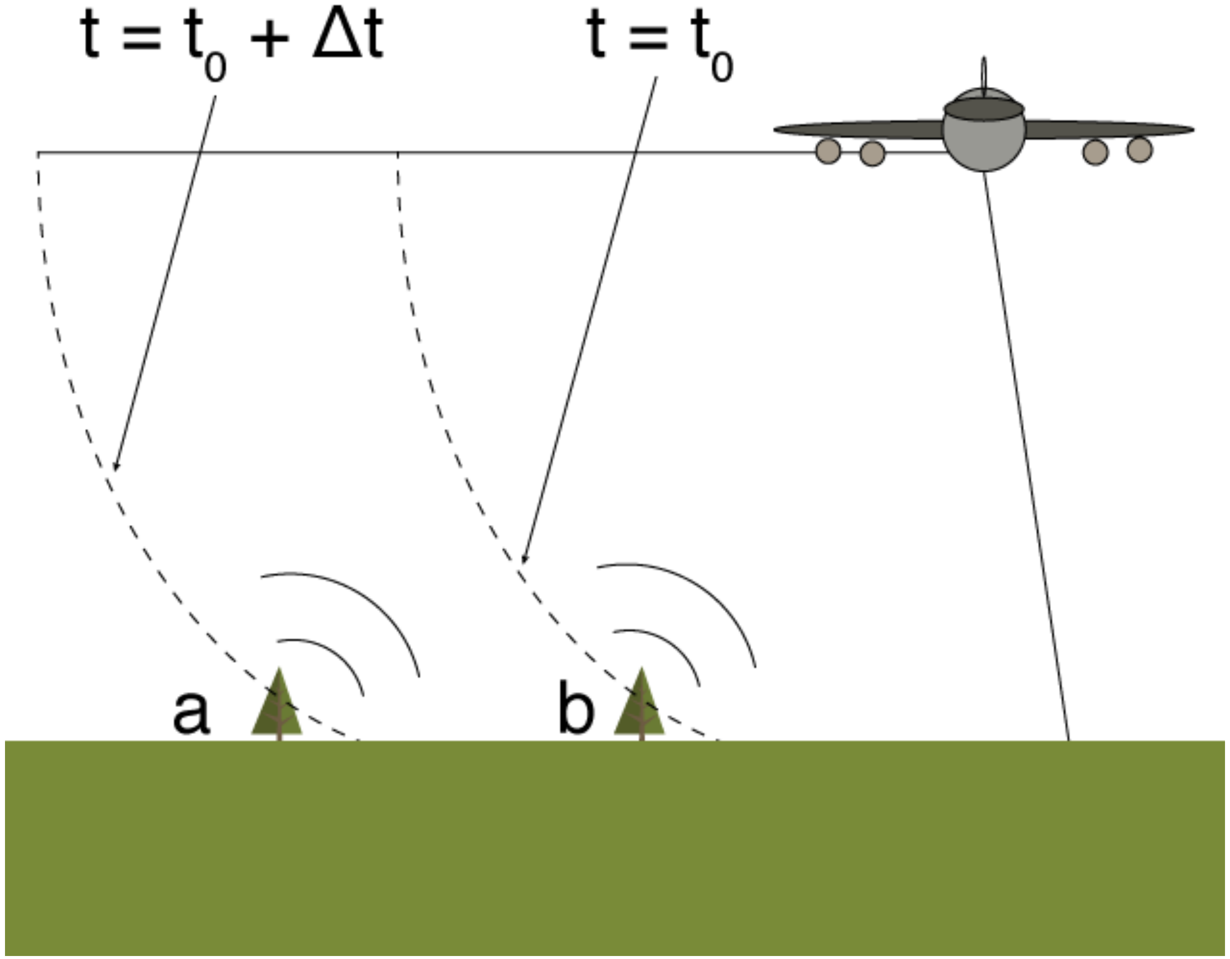
Image acquired by SIR-C/X-SAR aboard the Space Shuttle Endeavour Oct 5, 1994. Red (L-band HH), Green (L-band HV), Blue (C-band HV)

Basic Remote Sensing System



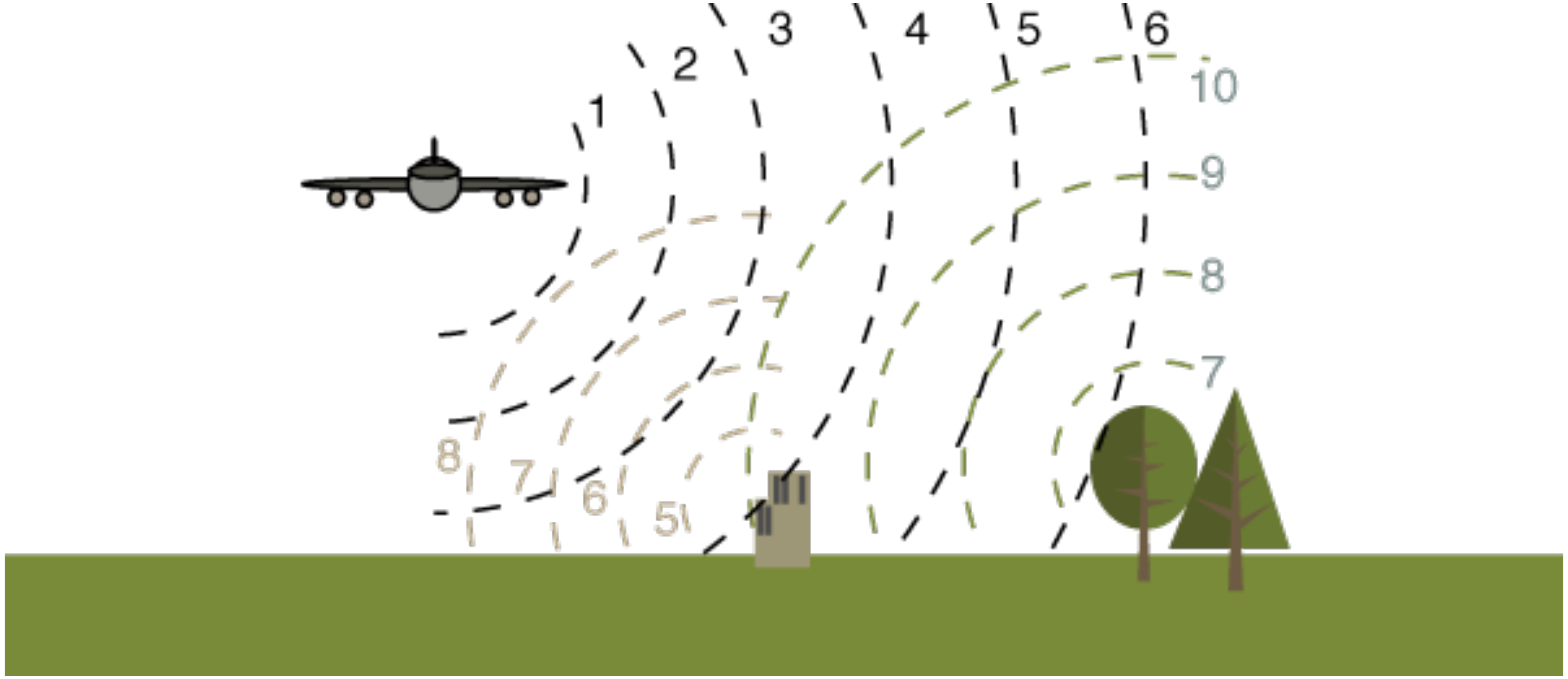
Basic Concepts: Down Looking vs. Side Looking Radar





Basic Concepts: Side Looking Radar

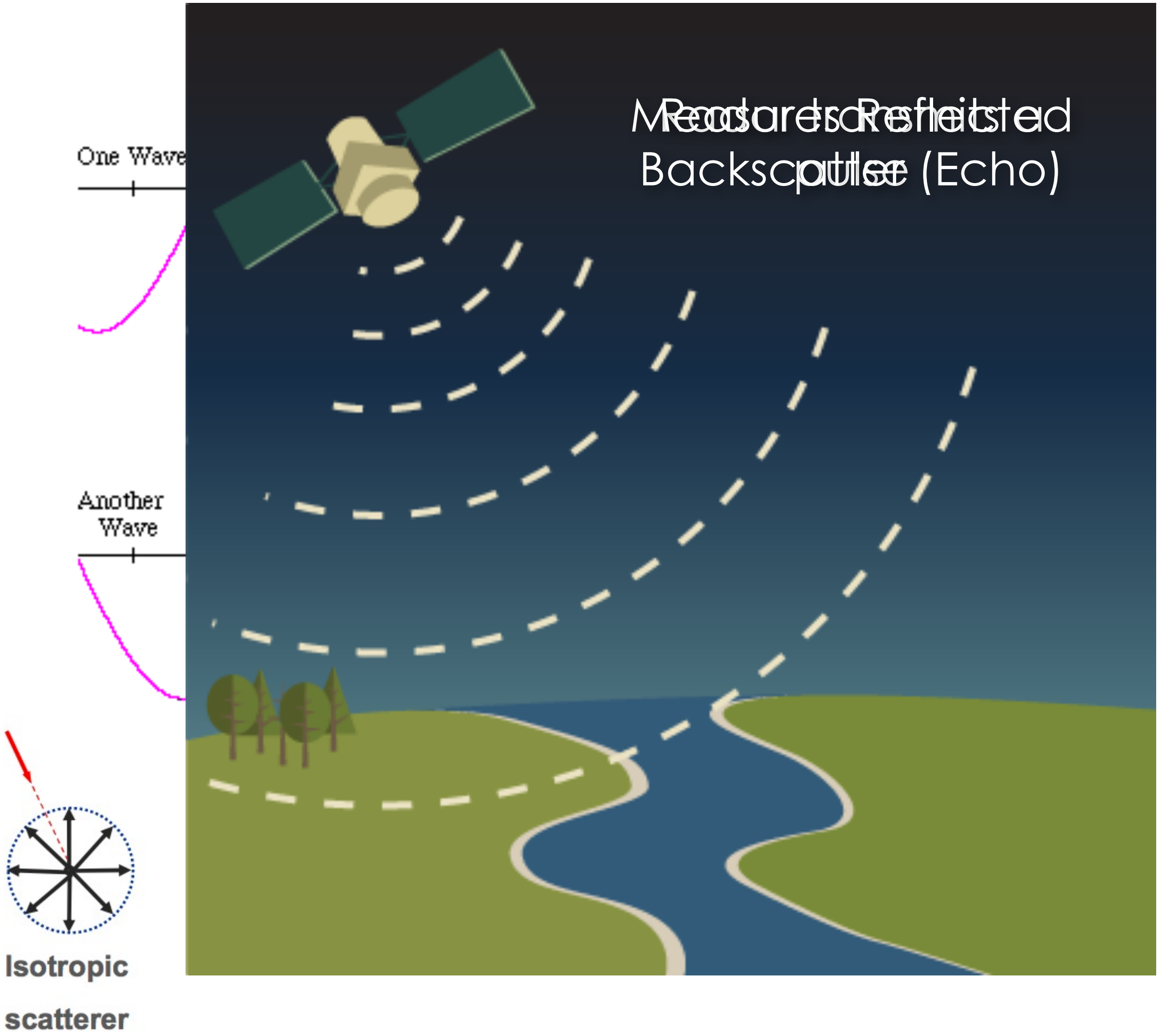
- Each pixel in the radar image represents a complex quantity of the energy that was reflected back to the satellite
- The magnitude of each pixel represents the intensity of the reflected signal



Credit: Paul Messina, CUNY NY, after Drury 1990, Lillesand and Kiefer, 1994

Review of Radar Image Formation

- Radar can measure amplitude (the strength of the reflected signal) and phase (the position of a point in time on a waveform cycle)
- Radar can only measure the part of the echo reflected back towards the antenna (backscatter)
- Radar pulses travel at the speed of light
- The strength of the reflected signal is the backscattering coefficient (sigma naught) and is expressed in decibels (dB)



Source: ESA- ASAR Handbook

Radar Parameters to Consider for a Study

- Wavelength
- Polarization
- Incidence Angle

Radar Parameters: Wavelength

$$\text{Wavelength} = \frac{\text{Speed of light}}{\text{Frequency}}$$

Higher Frequency

Shorter Wavelength

Lower Frequency

Longer Wavelength

Band designation*	Wavelength (λ), cm	Frequency (ν), GH_z (10^9 cycles $\cdot$ sec^{-1})
Ka (0.86 cm)	0.8 to 1.1	40.0 to 26.5
K	1.1 to 1.7	26.5 to 18.0
Ku	1.7 to 2.4	18.0 to 12.5
X (3.0 cm, 3.2 cm)	2.4 to 3.8	12.5 to 8.0
C (6.0)	3.8 to 7.5	8.0 to 4.0
S	7.5 to 15.0	4.0 to 2.0
L (23.5 cm, 25 cm)	15.0 to 30.0	2.0 to 1.0
P (68 cm)	30.0 to 100.0	1.0 to 0.3

*wavelengths most frequently used in SAR are in parenthesis

Radar Parameters: Wavelength

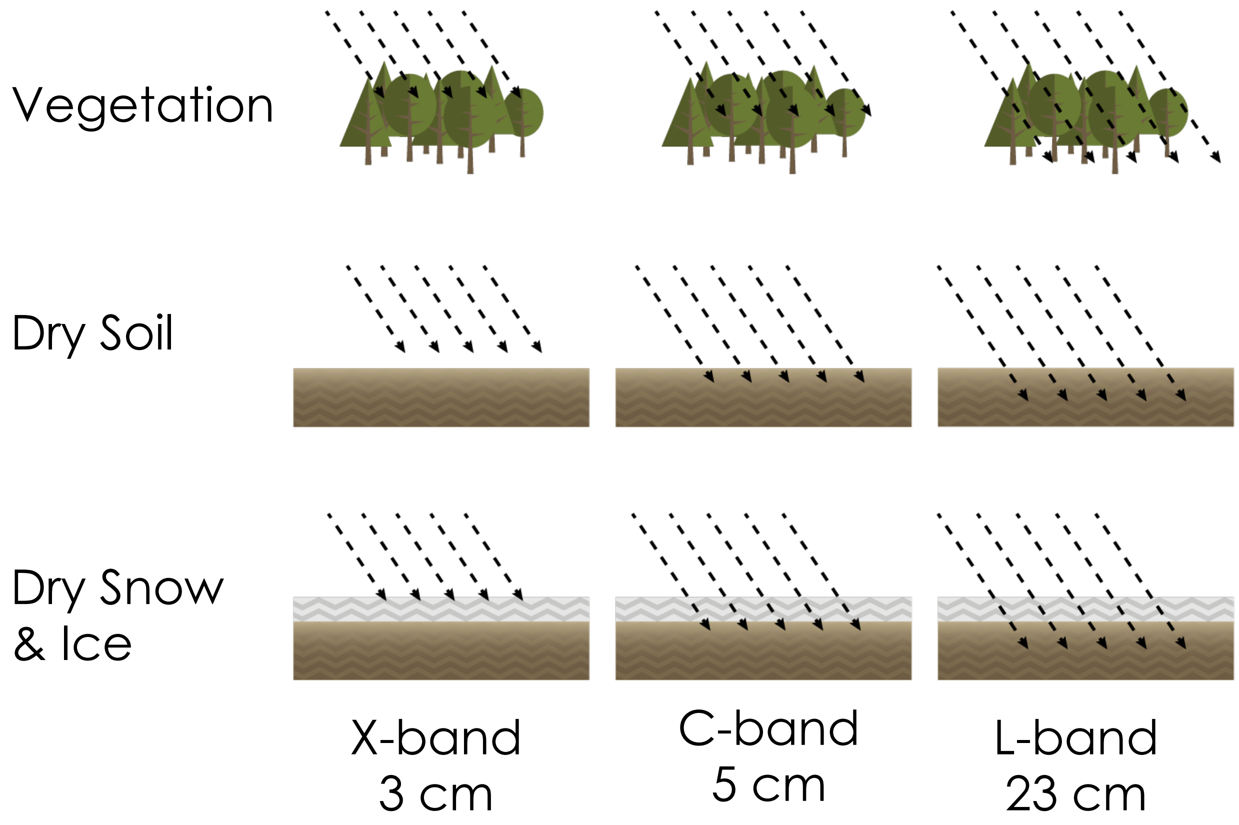
- Penetration is the **primary factor** in wavelength selection
- Penetration through the forest canopy or into the soil is greater with longer wavelengths

Commonly Used Frequency Bands

Frequency Band	Frequency Range	Application Example
VHF	300 KHz – 300 MHz	Foliage, ground penetration, biomass
P-Band	300 MHz – 1 GHz	biomass, soil moisture, penetration
L-Band	1 GHz – 2 GHz	agriculture, forestry, soil moisture
C-Band	4 GHz – 8 GHz	ocean, agriculture
X-Band	8 GHz – 12 GHz	agriculture, ocean, high resolution radar
Ku-Band	14 GHz – 18 GHz	glaciology (snow cover mapping)
Ka-Band	27 GHz – 47 GHz	high resolution radars

Table Reference: DLR

Penetration as a Function of Wavelength



- Waves can penetrate into vegetation and (in dry conditions) soil
- Generally, the longer the wavelength, the greater the penetration into the target

Image based on ESA Radar Course 2

Example: Radar Signal Penetration into Dry Soils

- Different satellite images over southwest Libya
- The arrows indicate possible fluvial systems

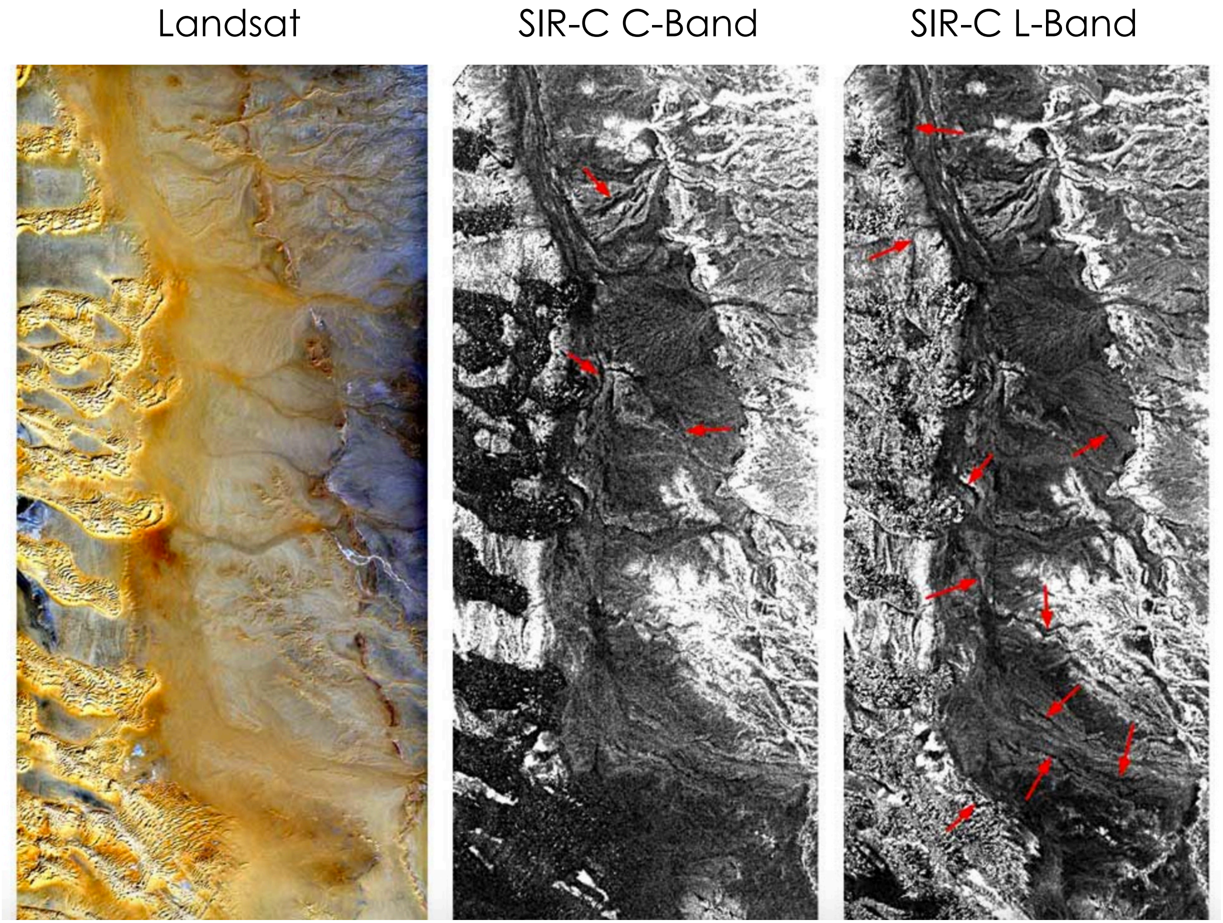
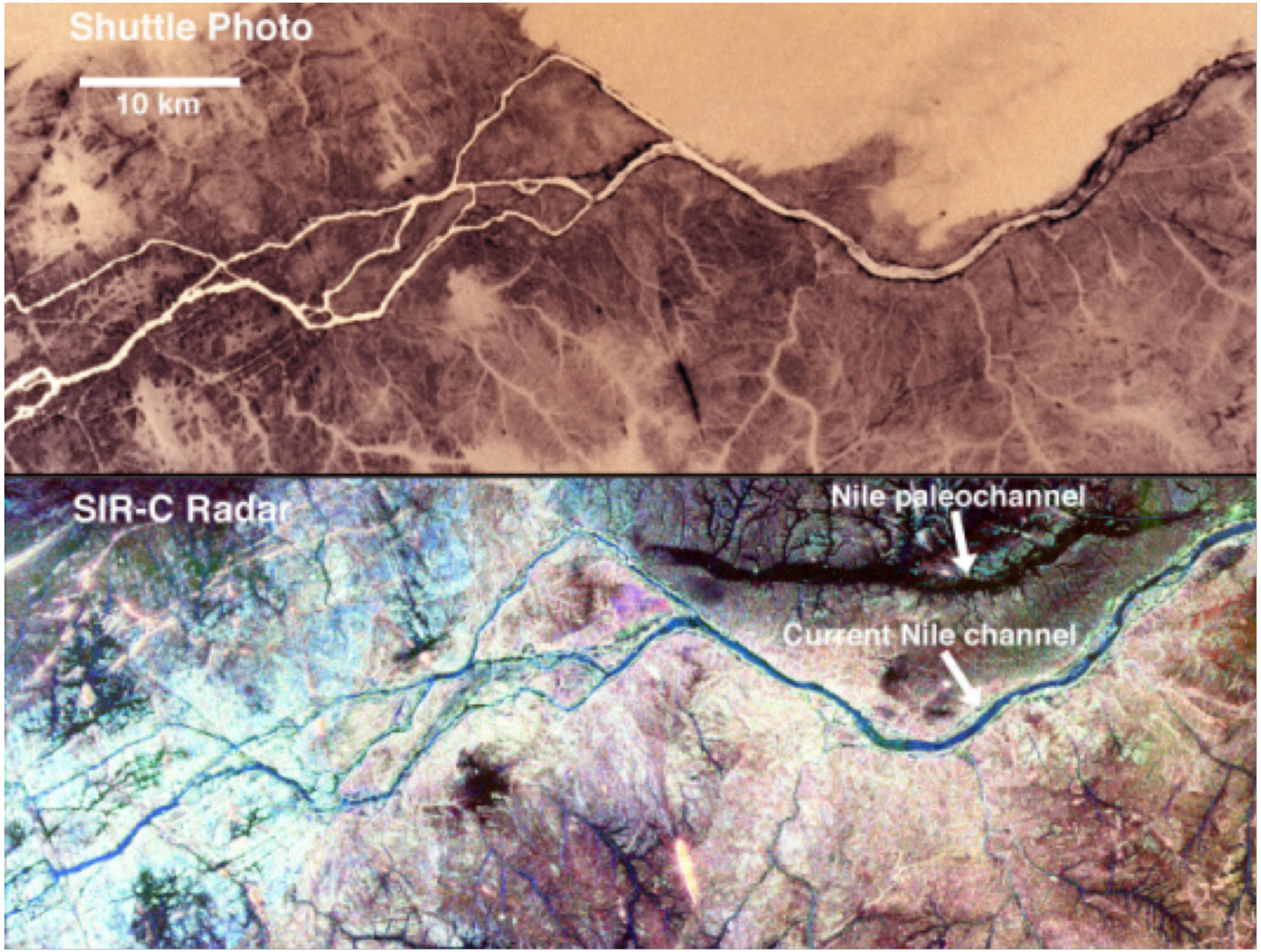


Image Credit: A Perego

Example: Radar Signal Penetration into Dry Soils



Example: Radar Signal Penetration into Vegetation

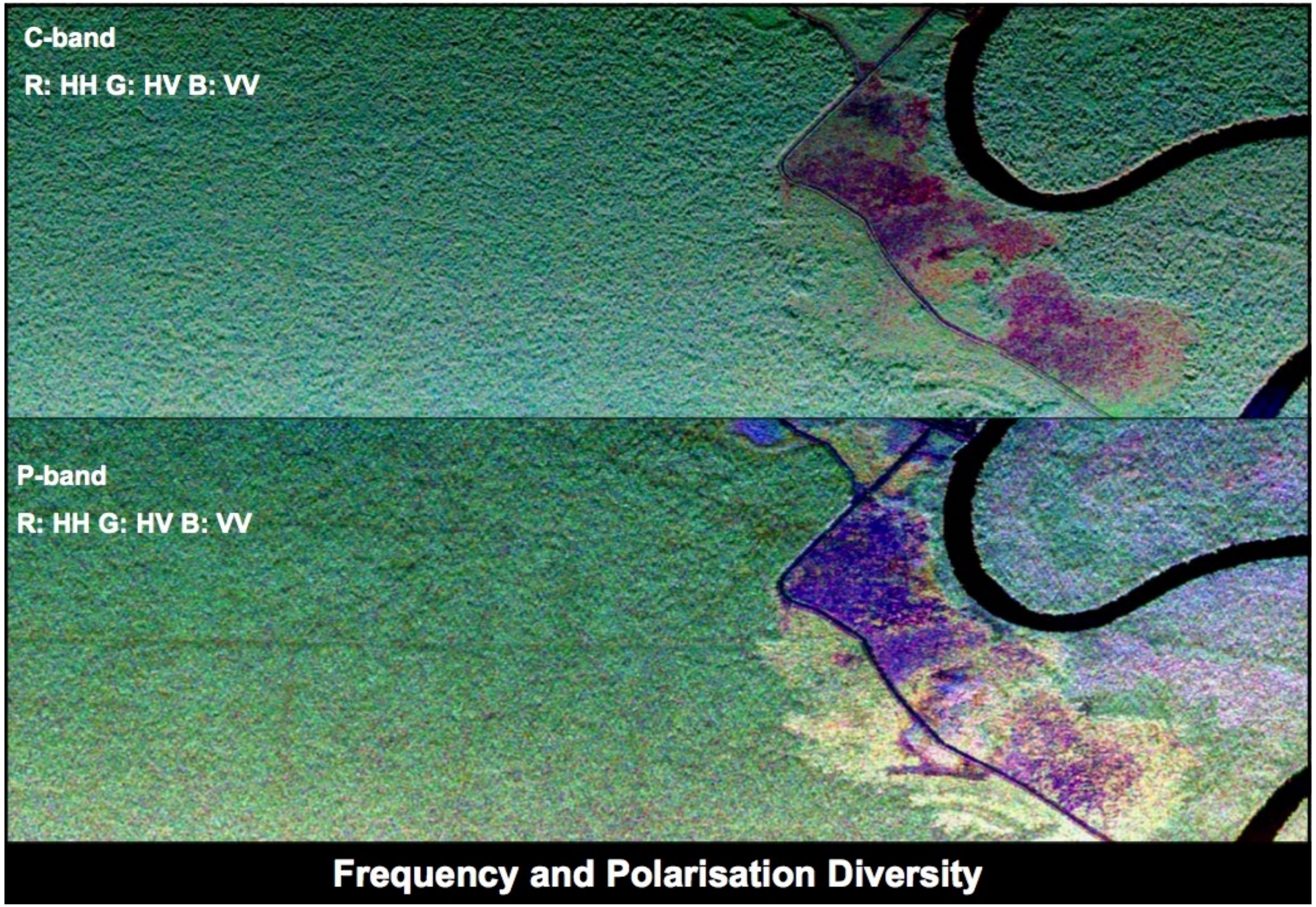
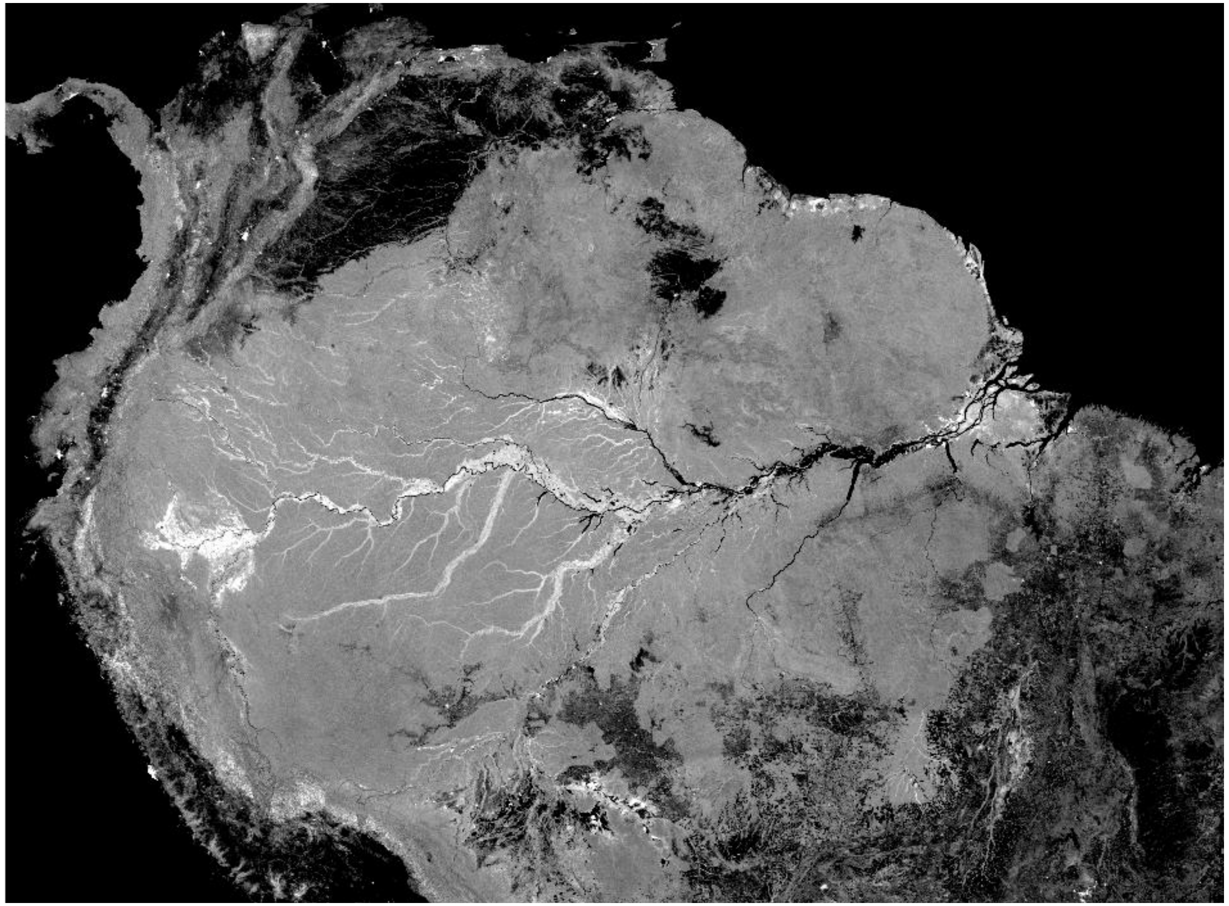


Image Credit: A Moreira - ESA

Example: Radar Signal Penetration into Wetlands

- L-band is ideal for the study of wetlands because the signal penetrates through the canopy and can sense if there is standing water underneath
- Inundated areas appear white in the image to the right

SMAP Radar Mosaic of the Amazon Basin April 2015 (L-band, HH, 3 km)



Radar Parameters: Polarization

- The radar signal is polarized
- The polarizations are usually controlled between H and V:
  - HH: Horizontal Transmit, Horizontal Receive
  - HV: Horizontal Transmit, Vertical Receive
  - VH: Vertical Transmit, Horizontal Receive
  - VV: Vertical Transmit, Vertical Receive

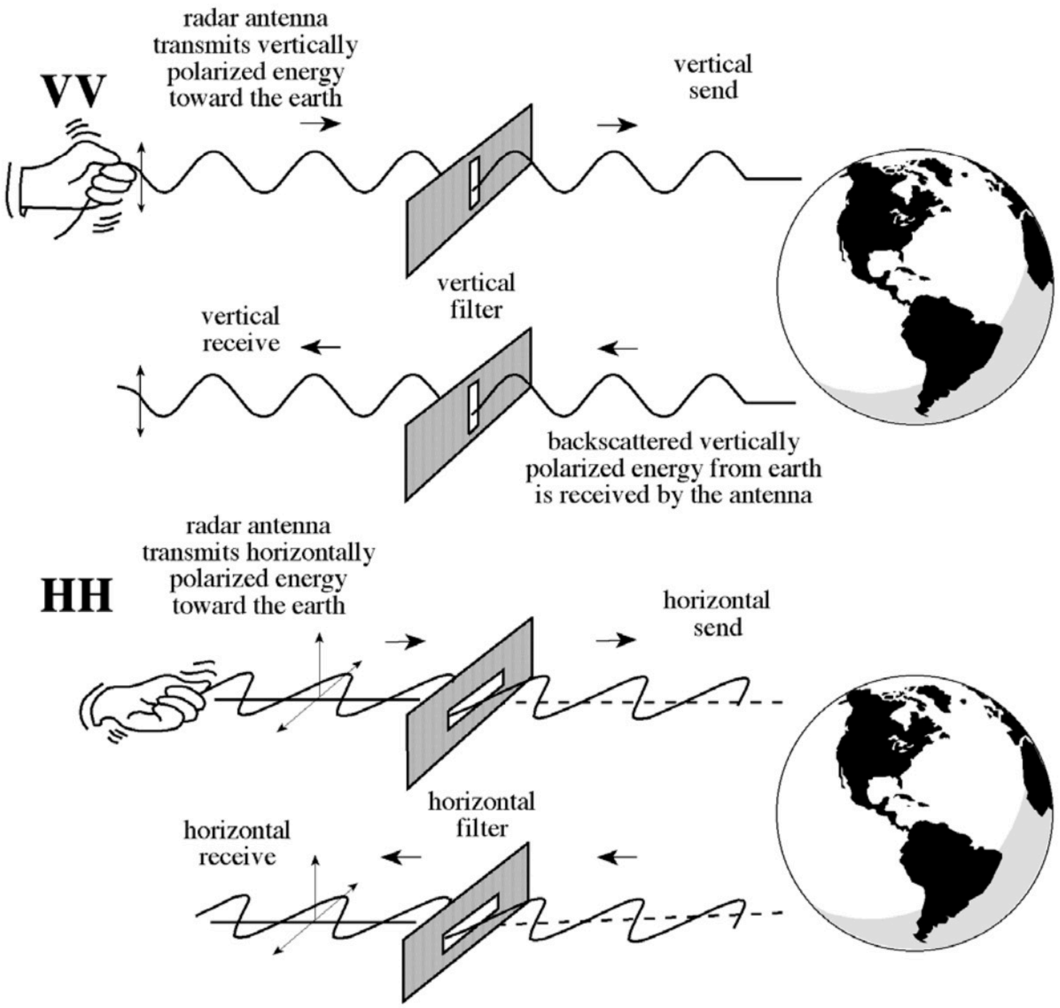


Image Credit: J.R. Jensen, 2000. Remote Sensing of the Environment

Radar Parameters: Polarization

- Quad-Pol Mode: when all four polarizations are measured
- Different polarizations can determine physical properties of the object observed

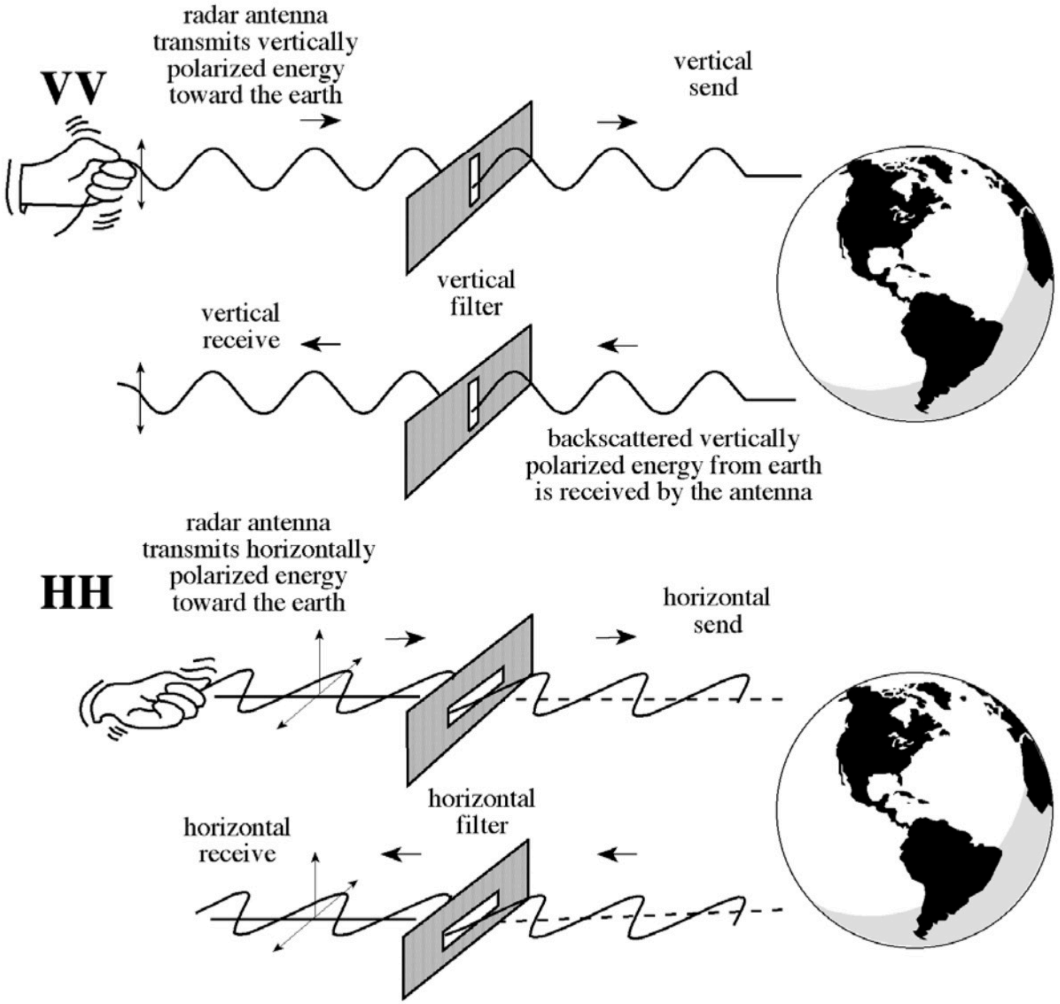
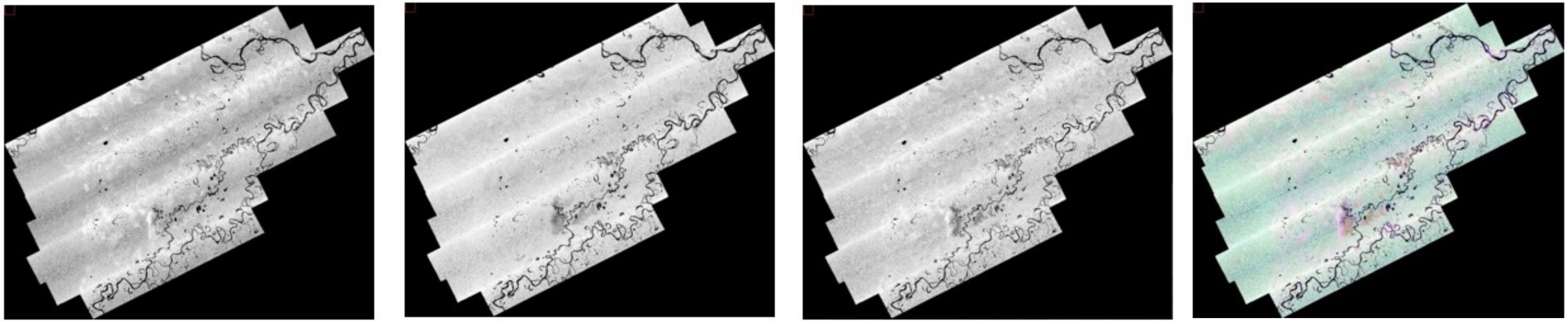


Image Credit: J.R. Jensen, 2000. Remote Sensing of the Environment

Example of Multiple Polarizations for Vegetation Studies

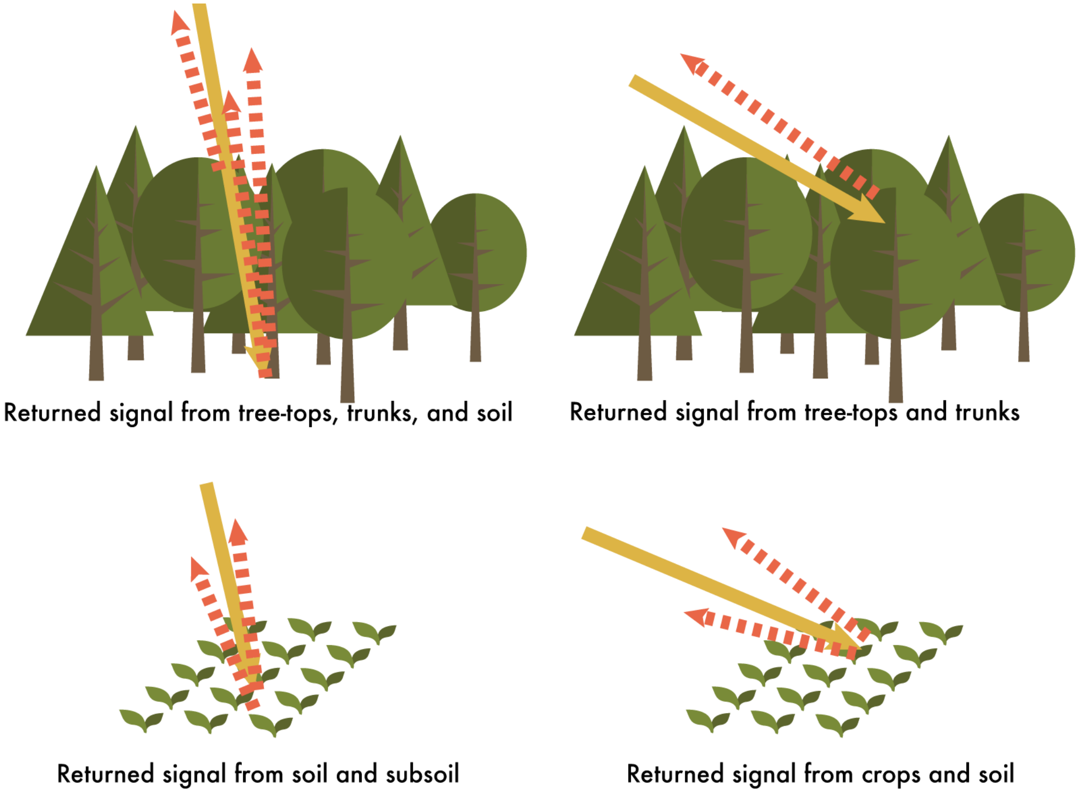
Pacaya-Samiria Forest Reserve in Peru

Images from UAVSAR (HH, HV, VV)



Radar Parameters: Incidence Angle

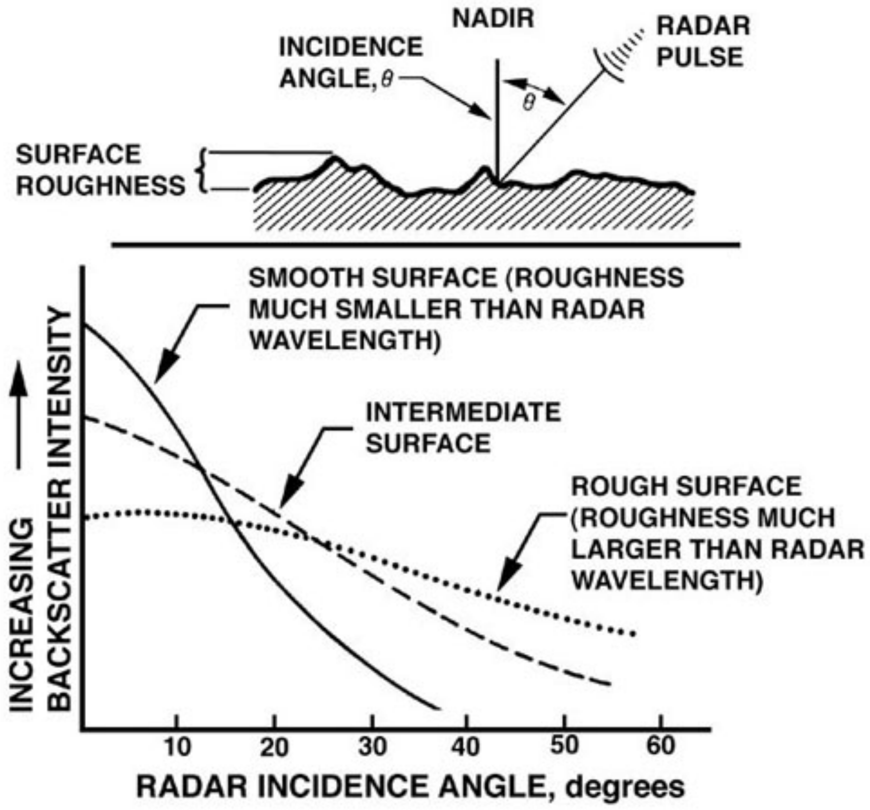
- The angle between the direction of illumination of the radar and the Earth's surface plane
- Depending on the height of the sensor, the incidence angle will change
- This is why the geometry of an image is different from point to point in the range direction
- Local Incidence Angle:
  – accounts for local inclination of the surface
  – influences image brightness



Images Based on:
(Above)Ulaby et al. (1981a), (Left) ESA

Radar Parameters: Incidence Angle

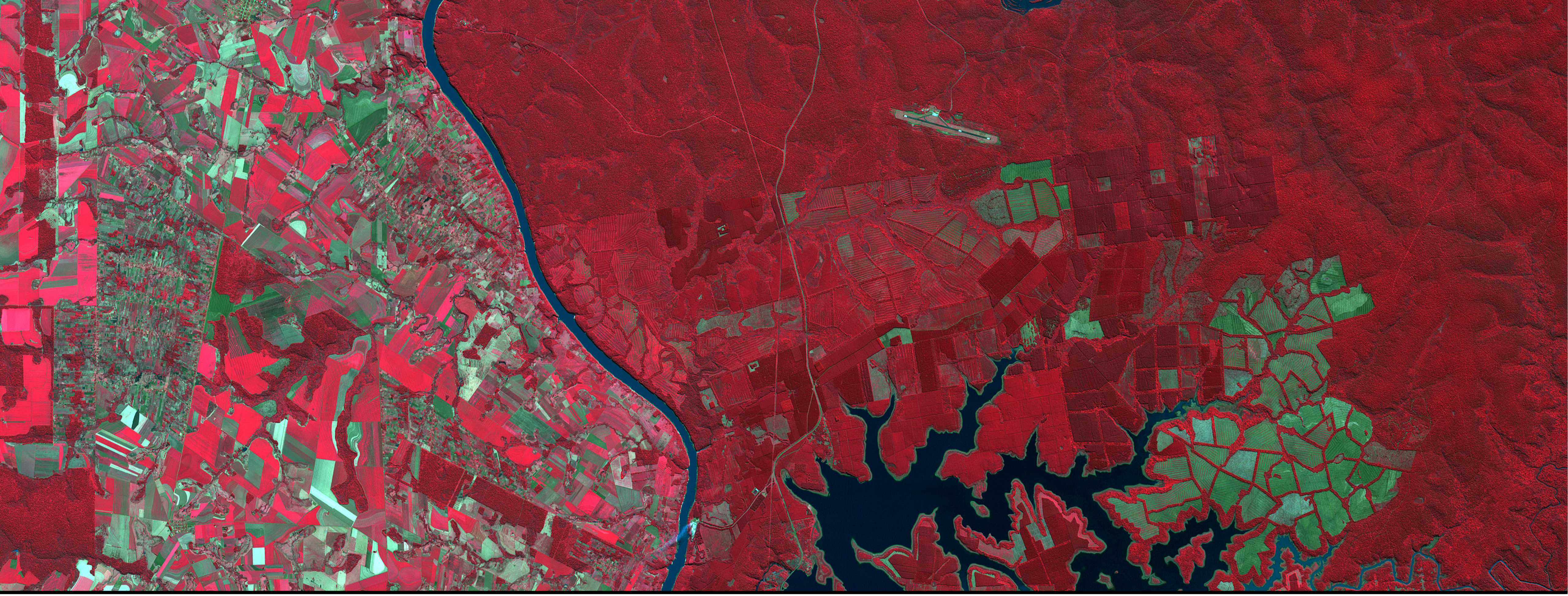
- Returns from surface scattering:
  - strong at low incidence angle
  - decrease with increasing incidence angle
  - slower rate of decrease the rougher the surface
- Returns due to volume scattering (rough surface):
  - more uniform for all incidence angles
- Radar backscatter is dependent on incidence angle
- This allows you to choose the best configuration for different applications



Text Reference: ESA; Image Credit: Ulaby et al. (1982b)

Questions

1. What are the advantages of radar sensors?
2. What are three main radar parameters that need to be considered for a specific study?
3. What is the relationship between wavelength and penetration?
4. What's the usefulness of having different polarizations?
5. What's the effect of varying incidence angles?



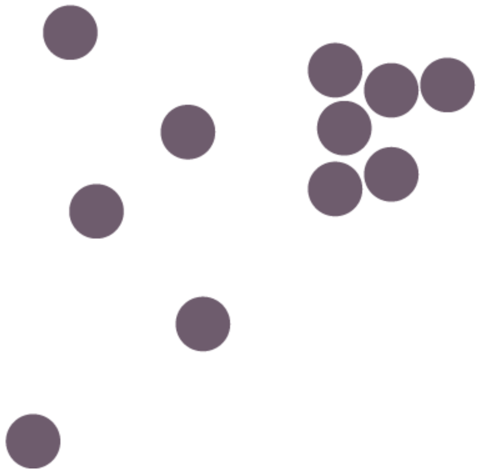
Radar Backscatter

Radar Backscatter

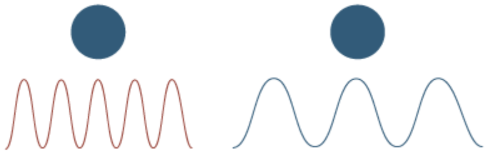
- The radar backscatter contains information about the Earth's surface, which drives the reflection of the radar signal
- This reflection is driven by:
  - The frequency or wavelength: radar parameter
  - Polarization: radar parameter
  - Incidence angle: radar parameter
  - Dielectric constant: surface parameter
  - Surface roughness relative to the wavelength: surface parameter
  - Structure and orientation of objects on the surface: surface parameter

Backscattering Mechanisms

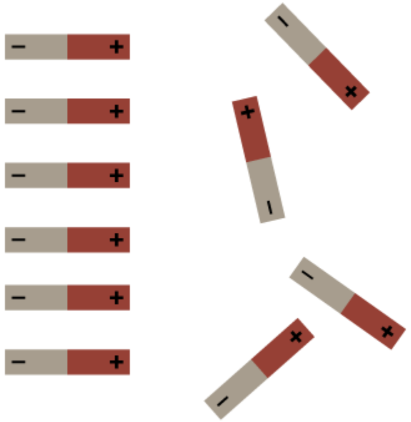
Density



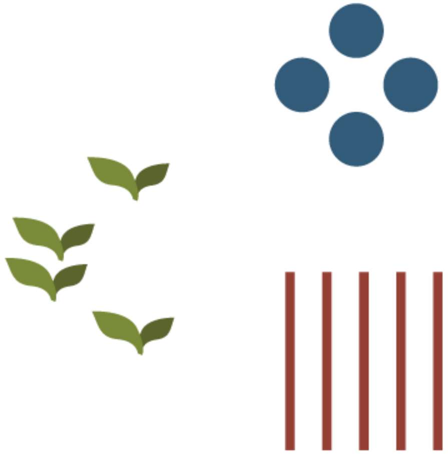
Size in relation to wavelength



Dielectric Constant

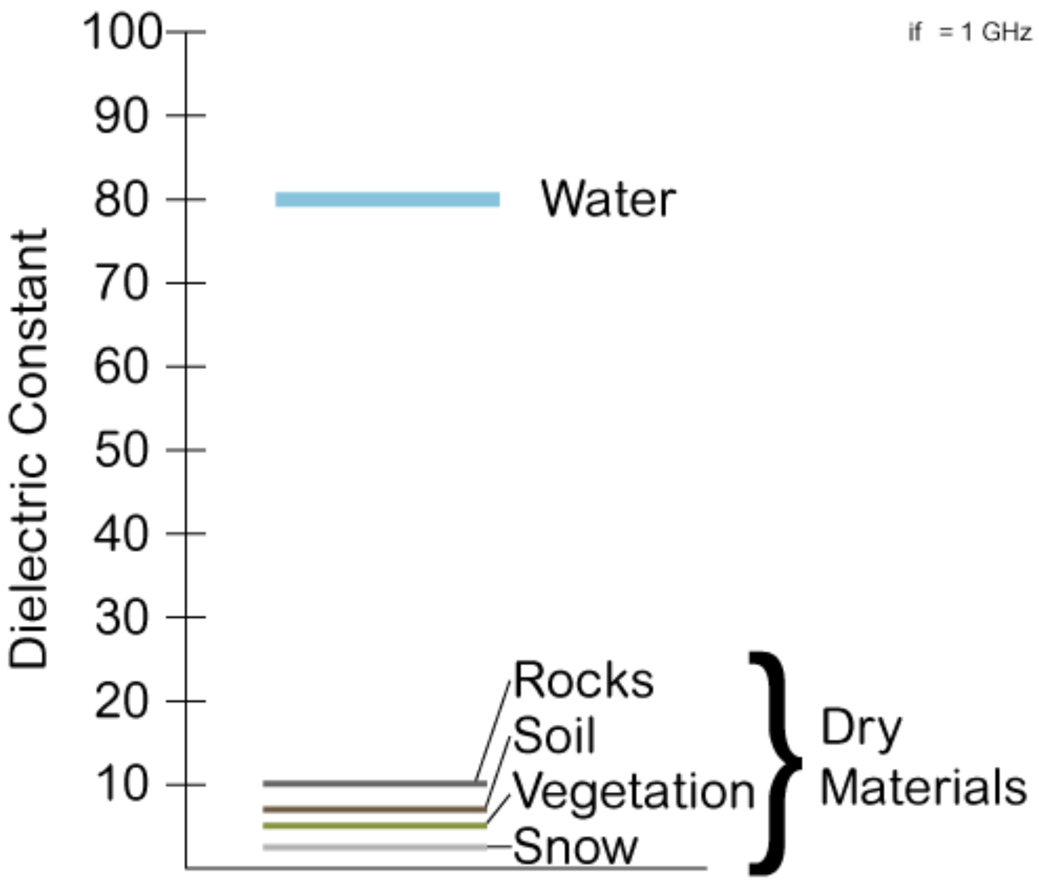


Size and Orientation

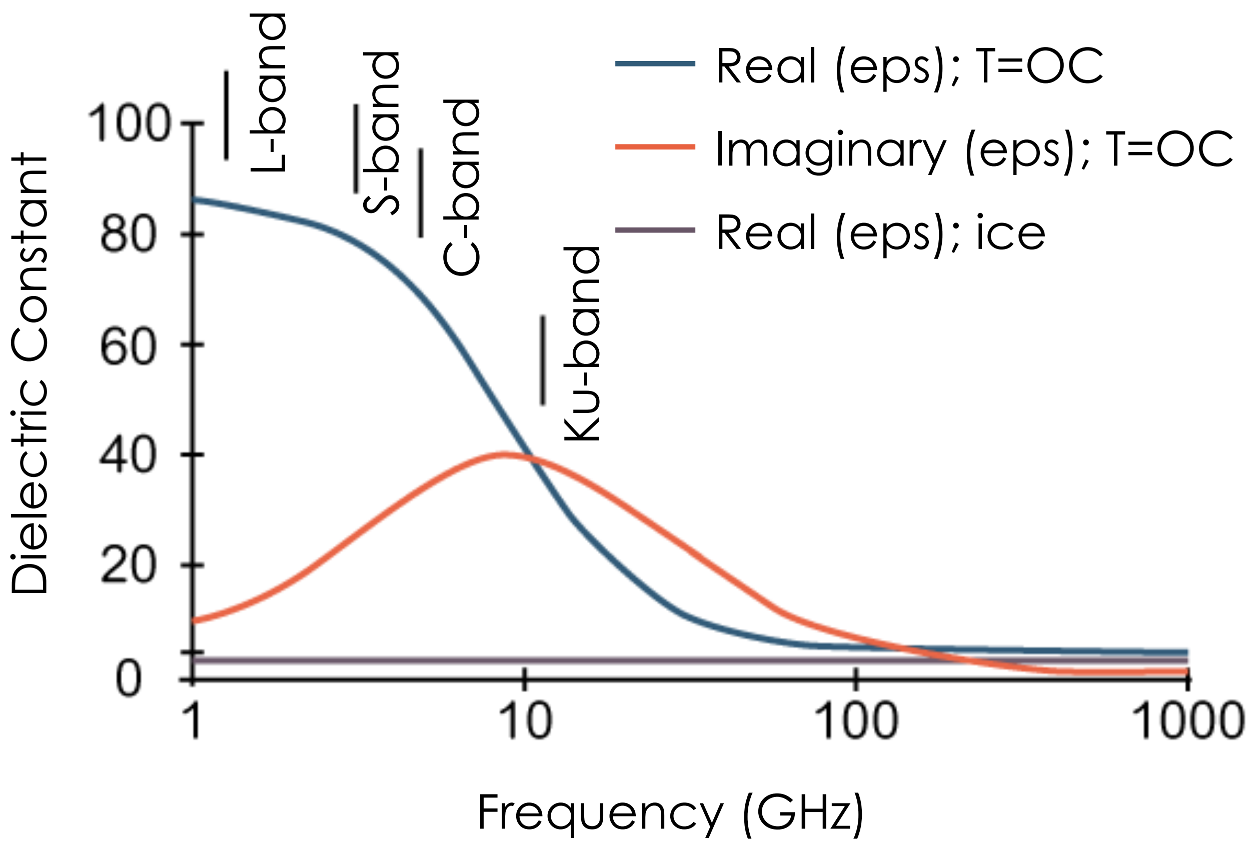


Surface Parameters: Dielectric Constant

Dielectric Properties of Materials



Dielectric Constant vs. Frequency



Dielectric Properties of the Surface and its Frozen or Thawed State

- During the land surface freeze/thaw transition there is an increase in dielectric properties of the surface
- This causes a notable increase in backscatter

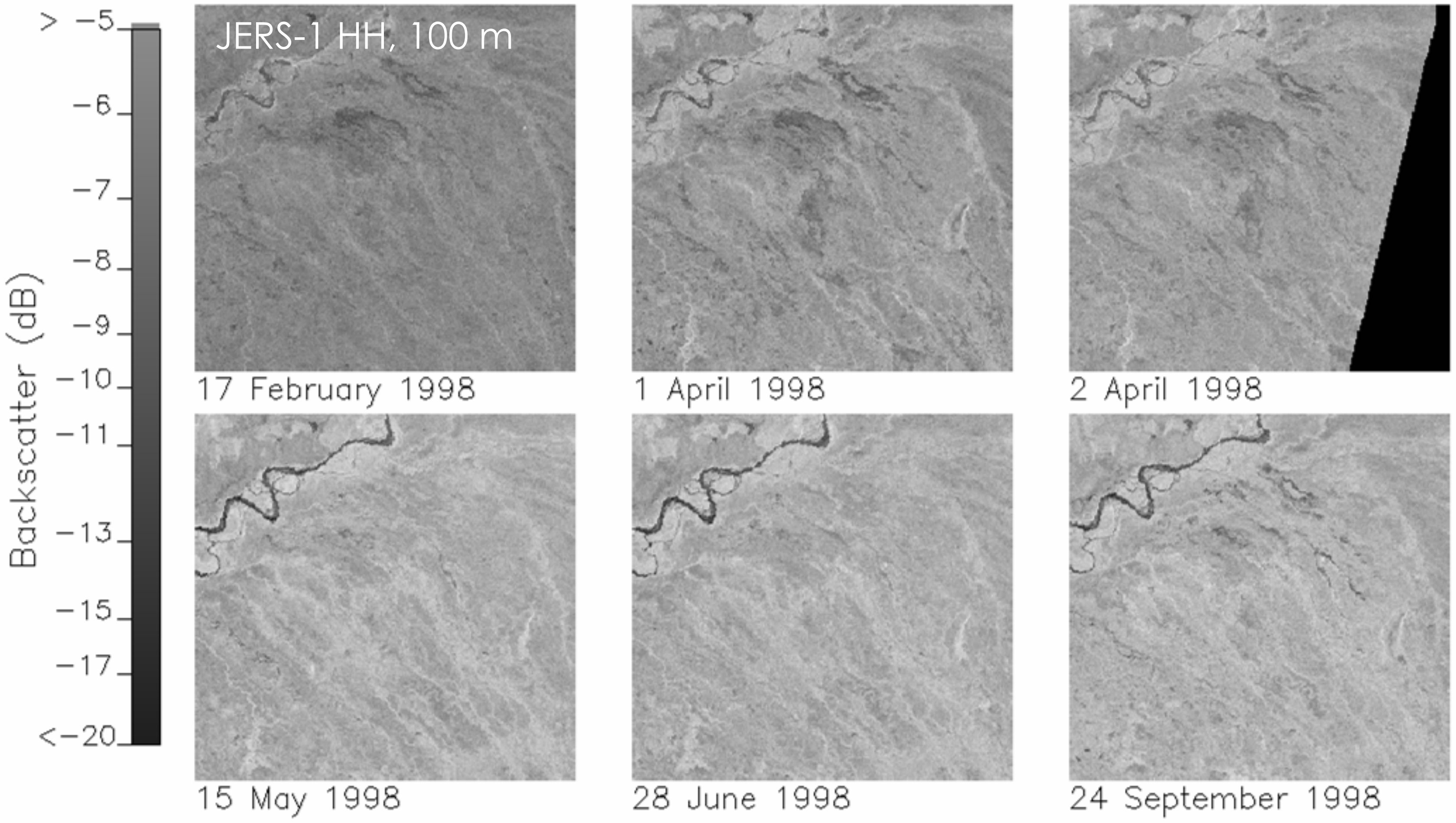
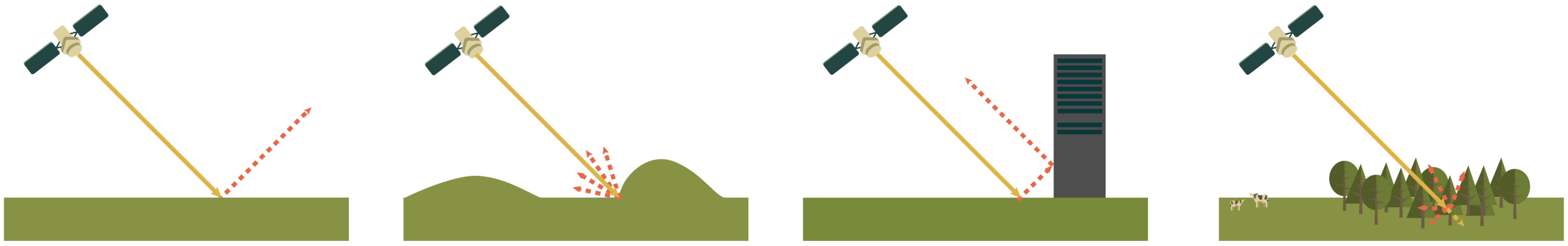


Image Credit: Erika Podest

Radar Signal Interaction

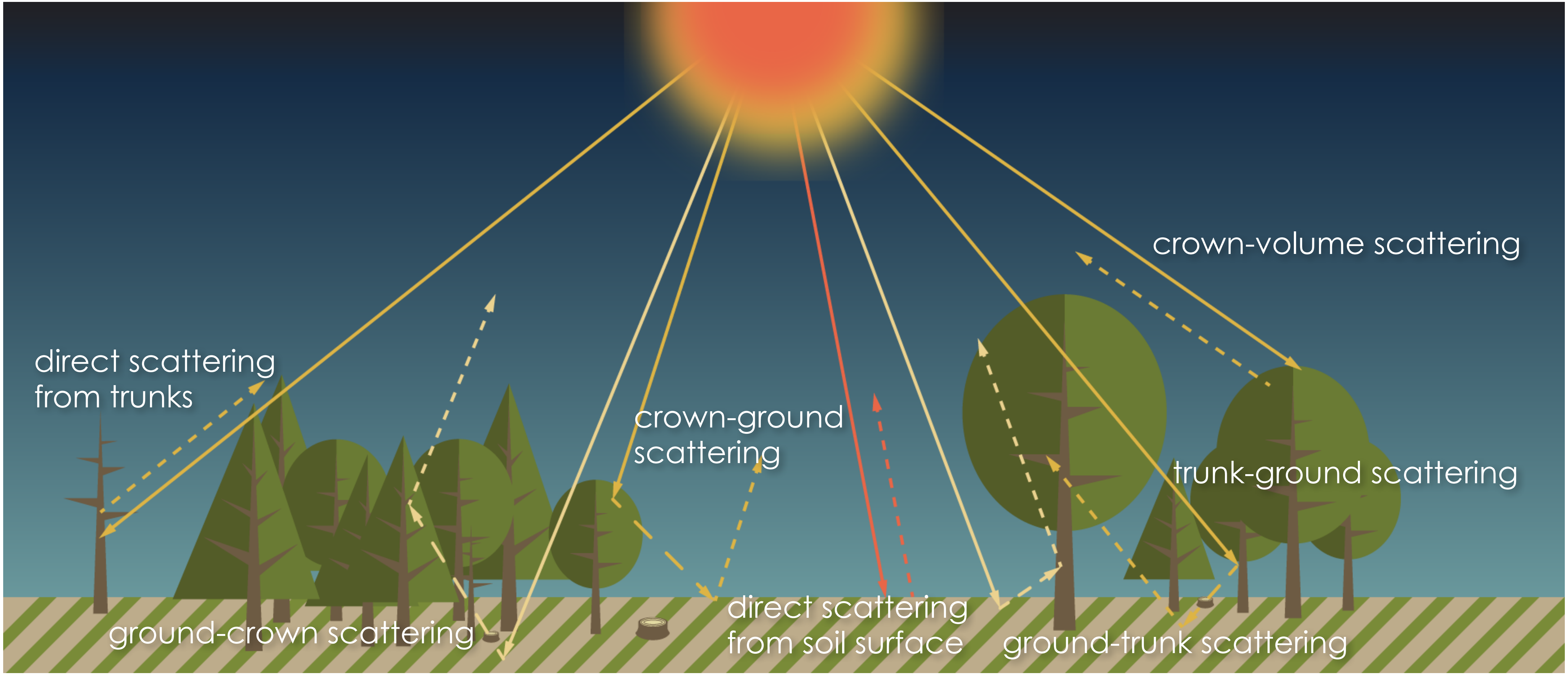
- The radar signal is primarily sensitive to surface structure
- A surface will appear rough or smooth relative to the scale of the variations of the surface to the wavelength. This will influence how bright (rough) or dark (smooth) the surface will appear on the image

Backscattering Mechanisms



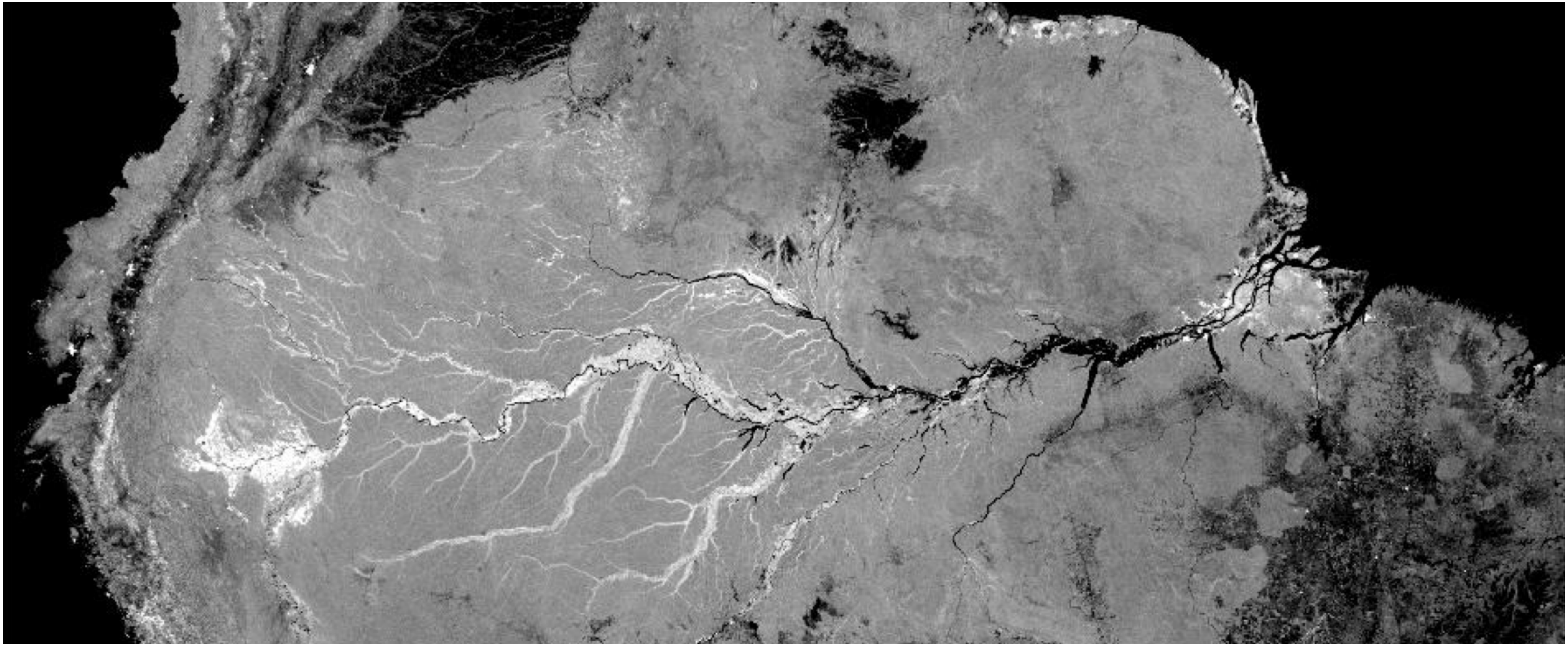
Smooth Surface　Rough Surface　Double Bounce　Vegetation Layer

Radar Backscatter in Forests



Examples of Radar Interaction

SMAP Radar Mosaic of the Amazon Basin, April 2015 (L-band, HH, 3 km)



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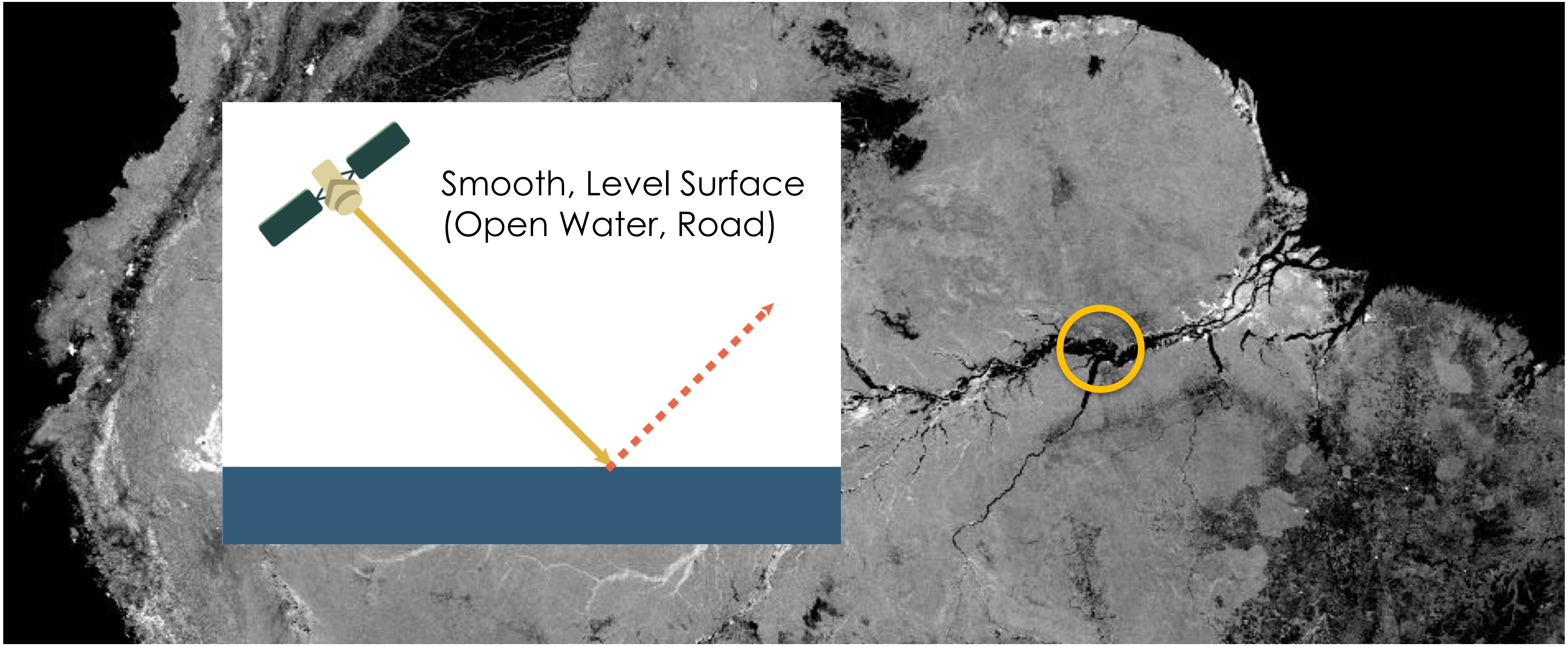

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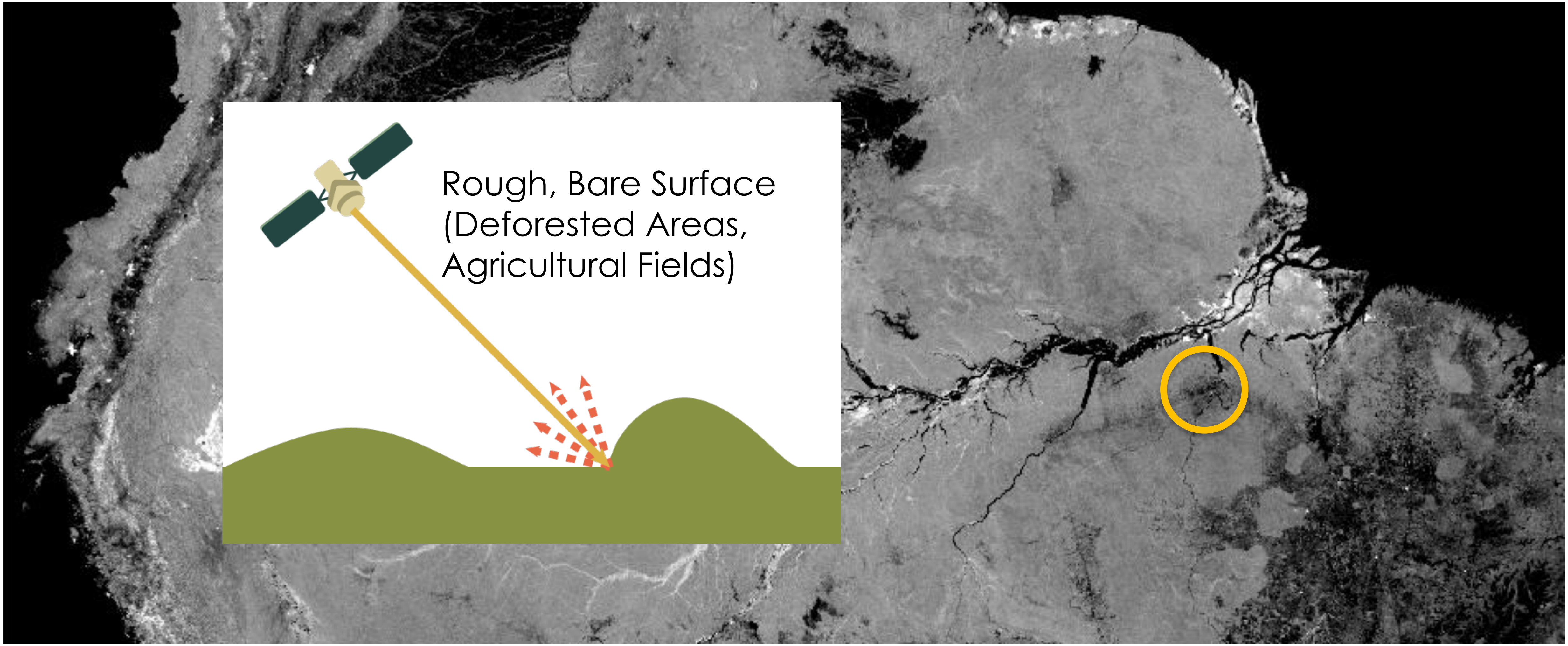

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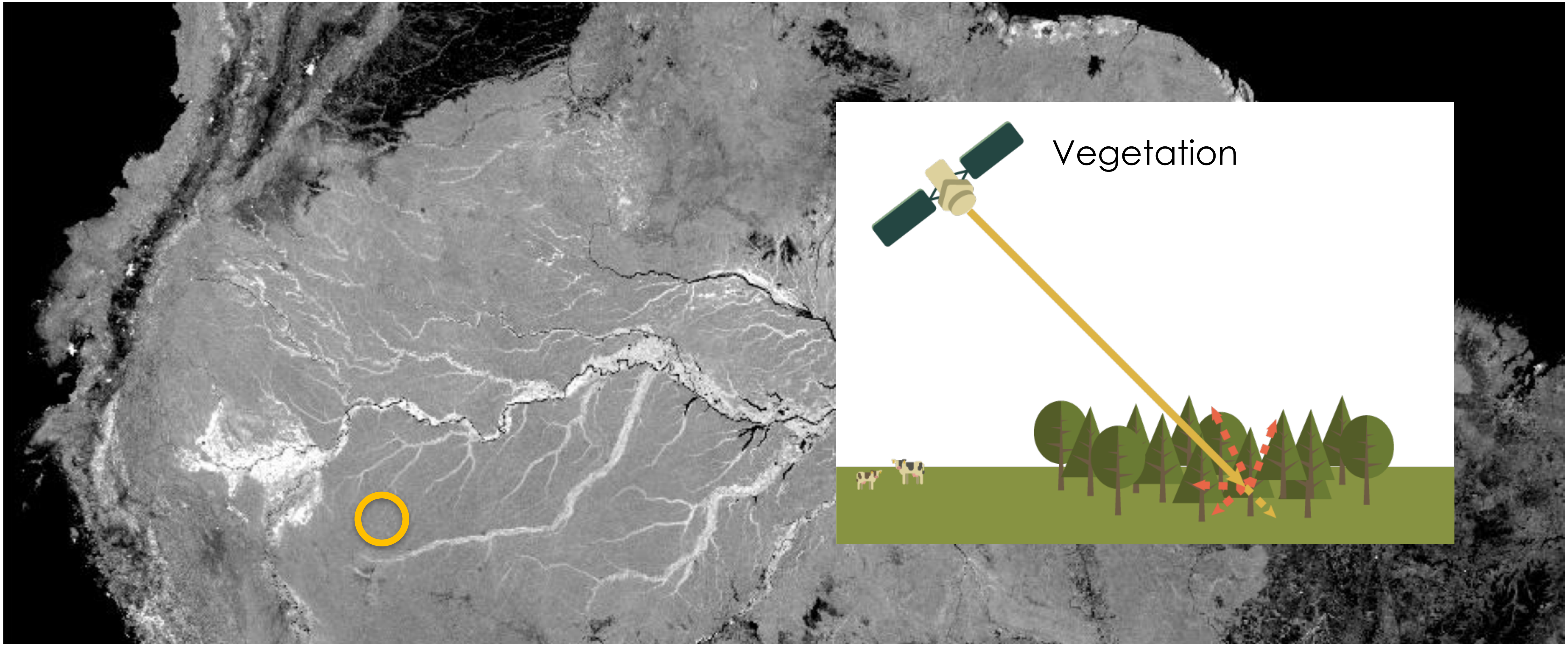

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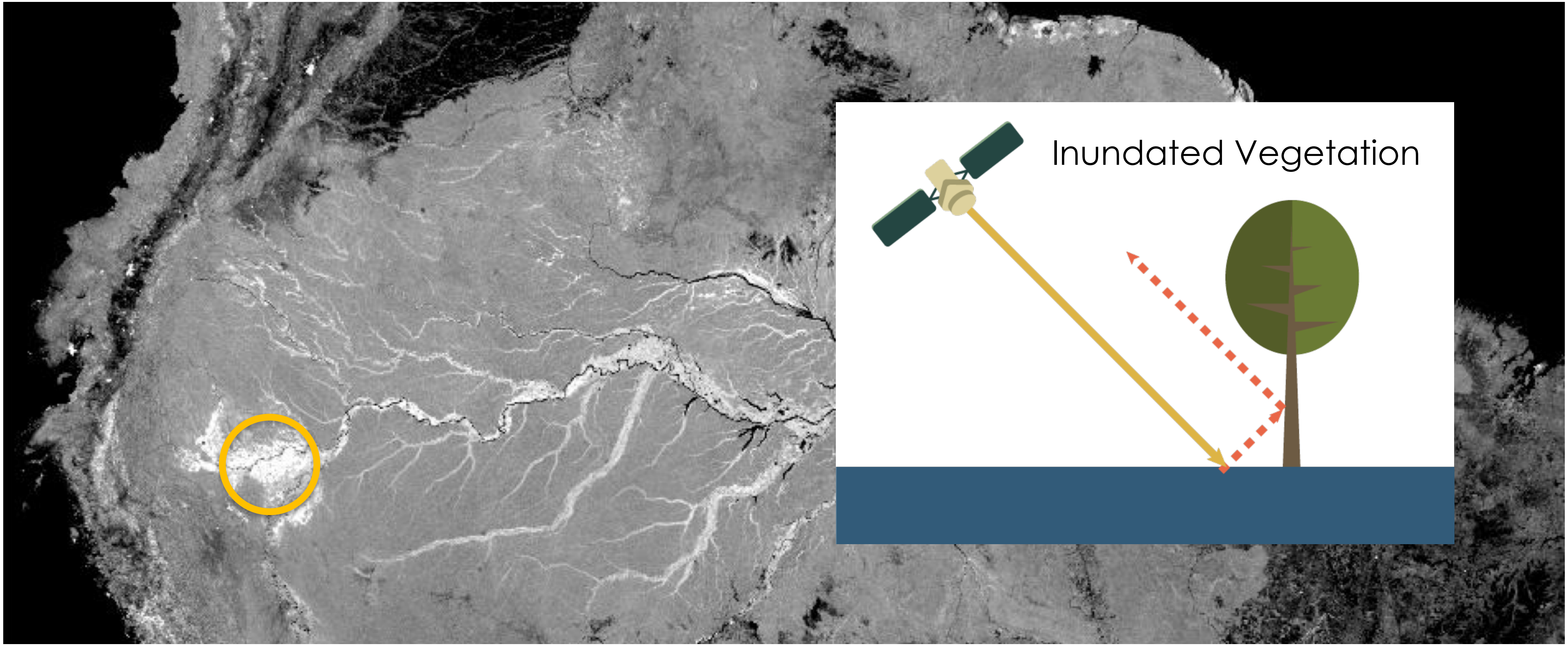
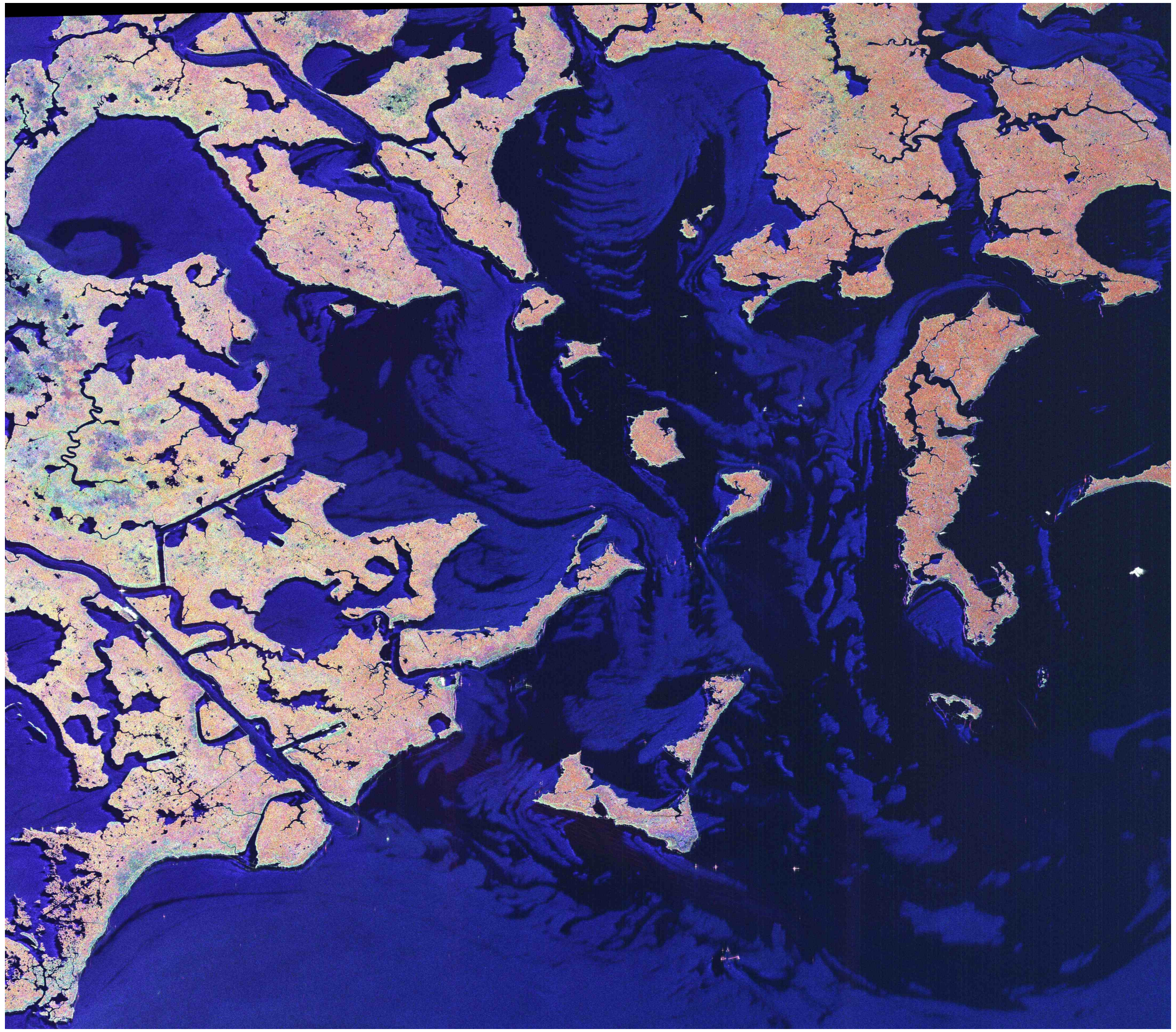
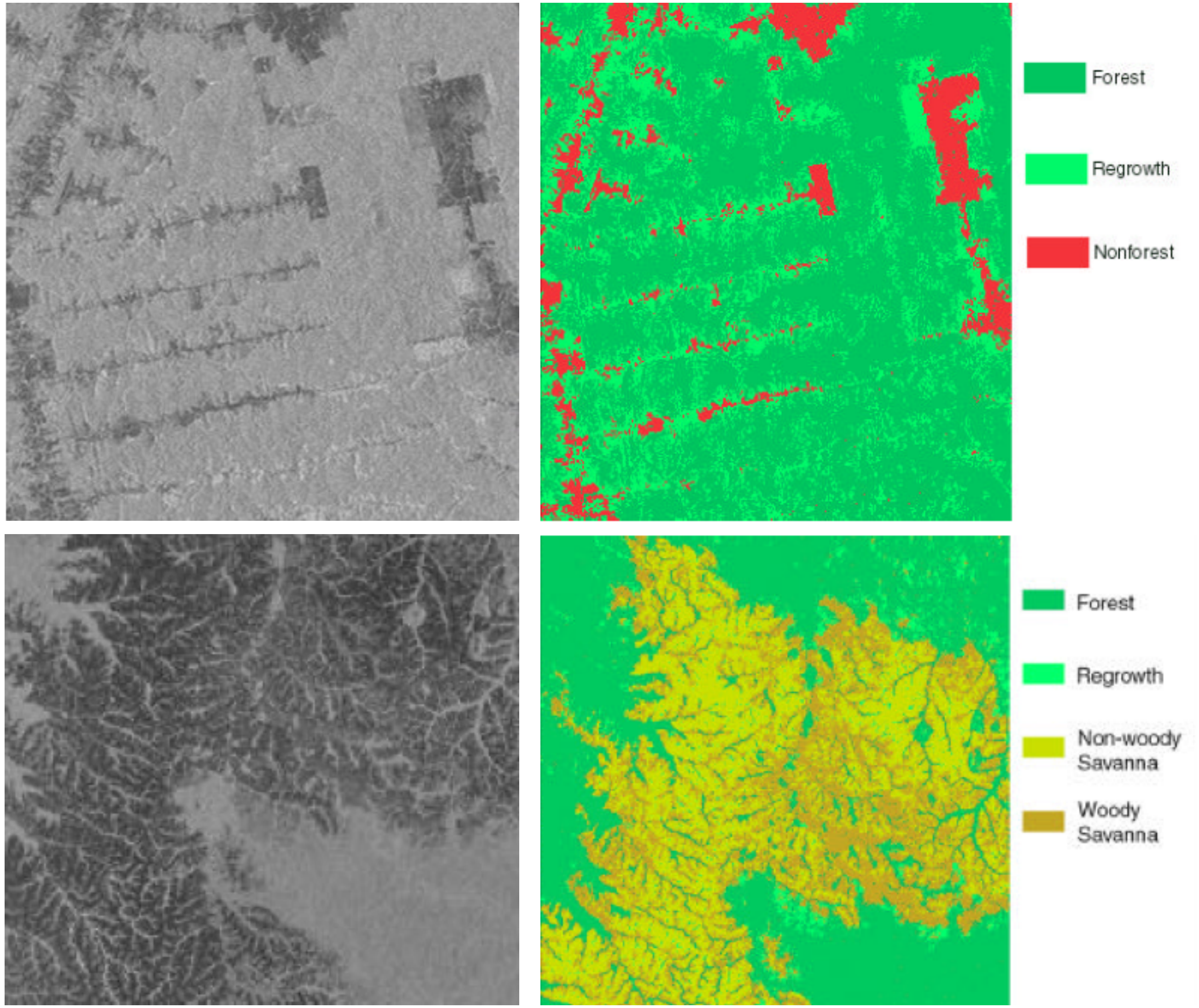


Example: Detection of Oil Spills on Water

UAVSAR (L-band, 2 meters): HH, HV, VV

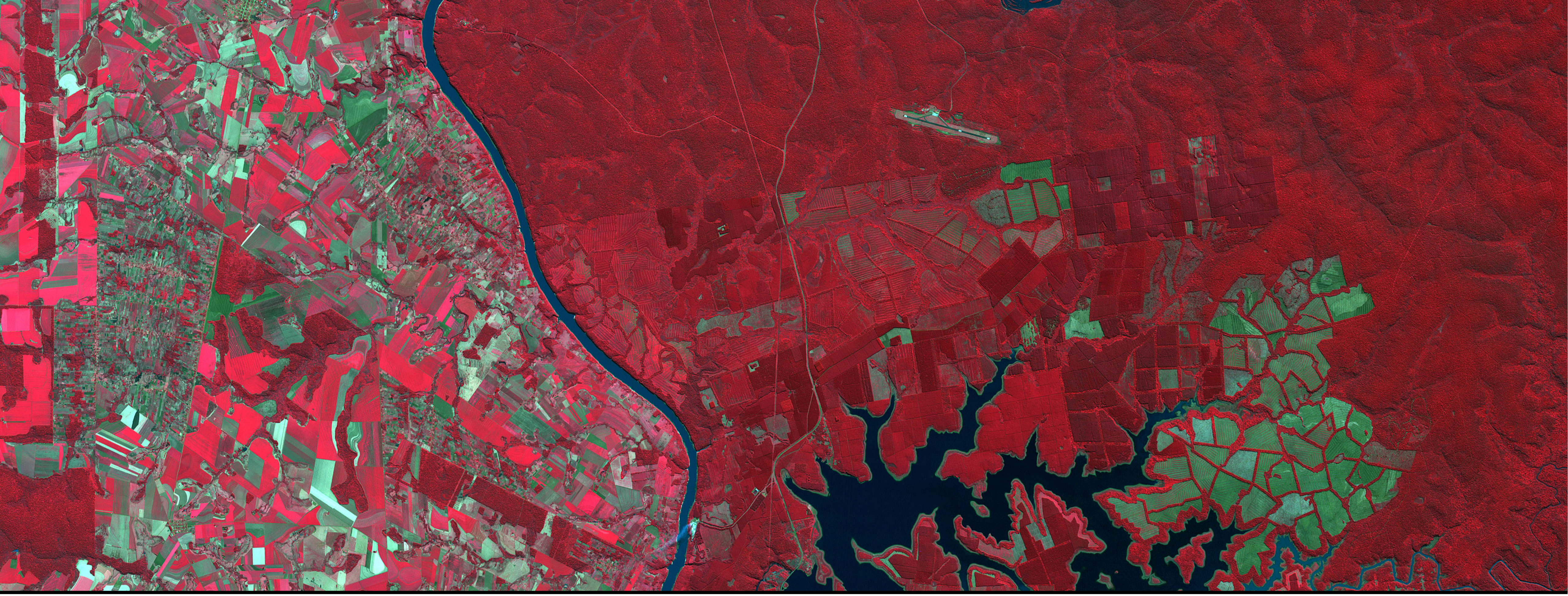


Example: Land Cover Classification



- Brazil
- JERS-1 L-band
- HH, 100 meter resolution

Credit: Podest, et al. "Application of Multiscale Texture in Classifying JERS-1 Data over Tropical Vegetation", *Int. Jour. Rem. Sens.*, 2002.

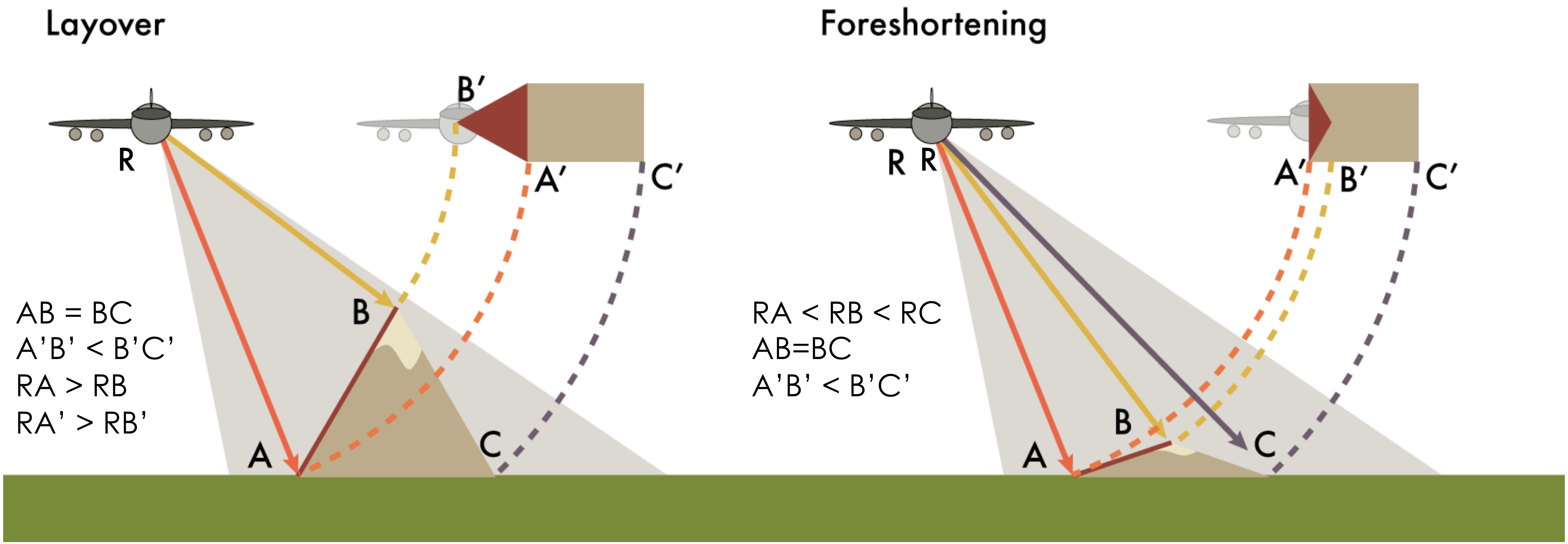


Geometric and Radiometric Distortion of the Radar Signal

Slant Range Distortion

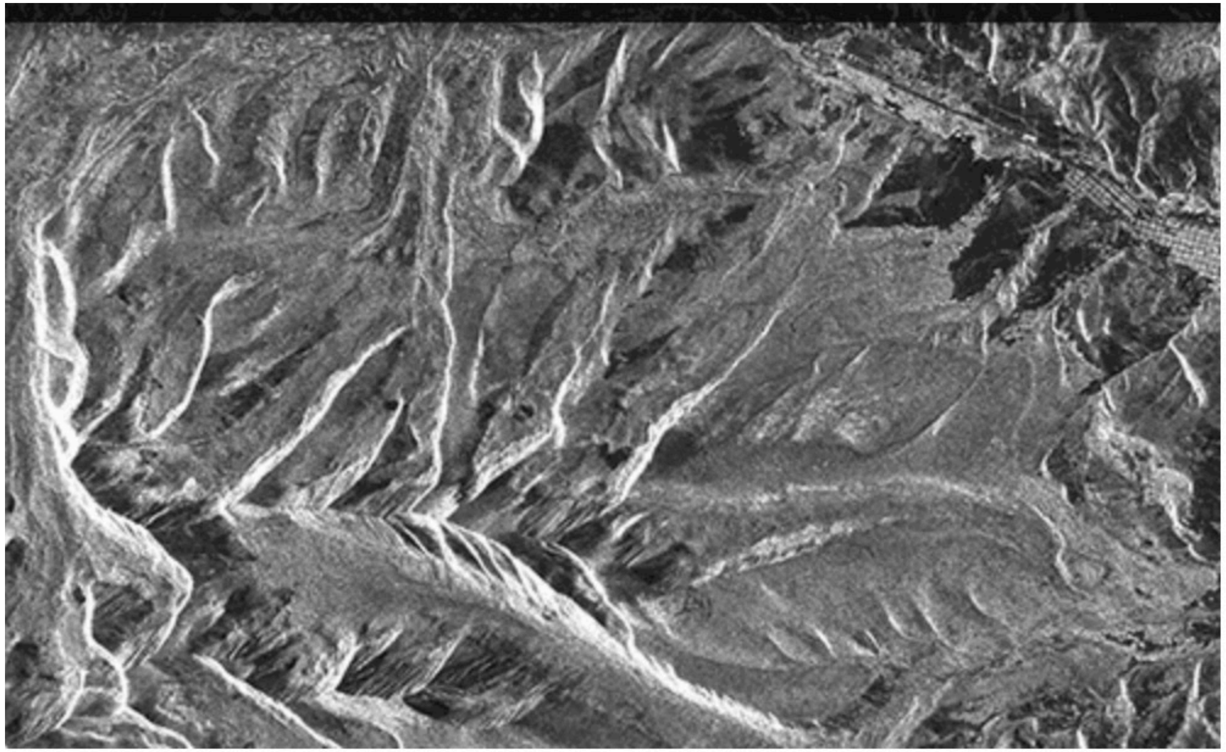
Source: Natural Resources Canada

Geometric Distortion

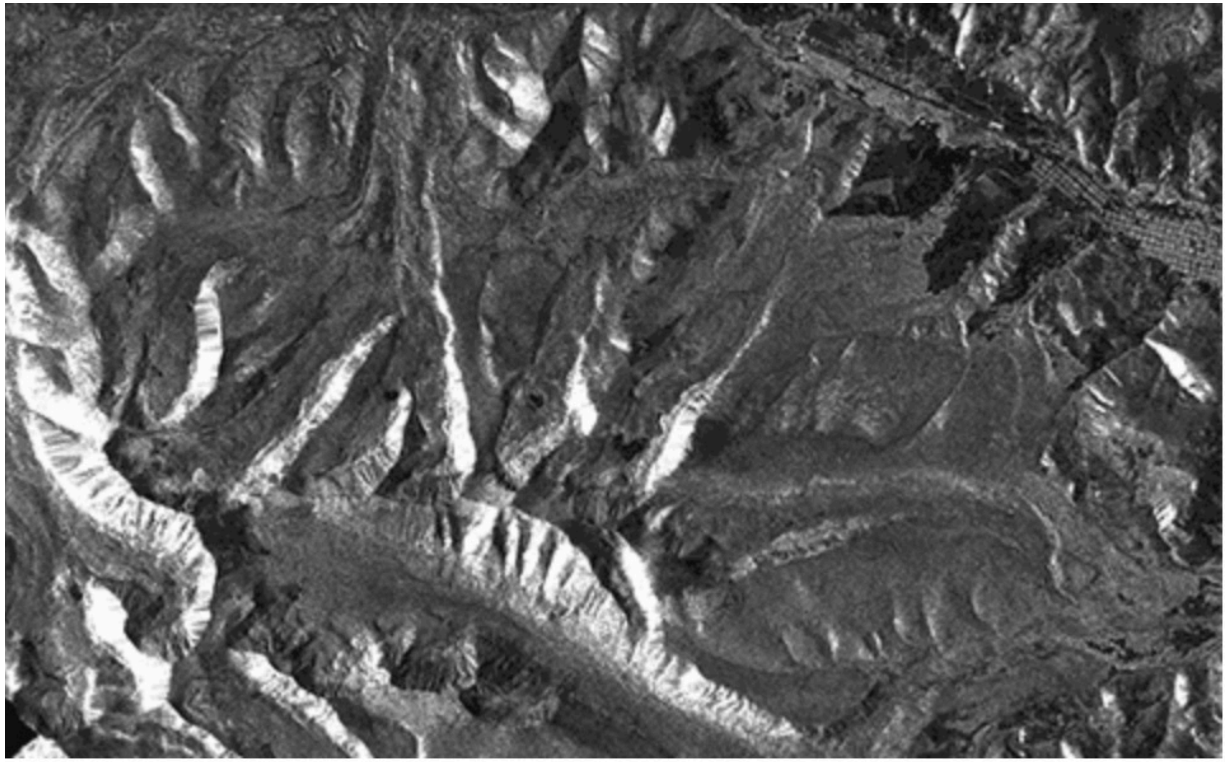


Foreshortening

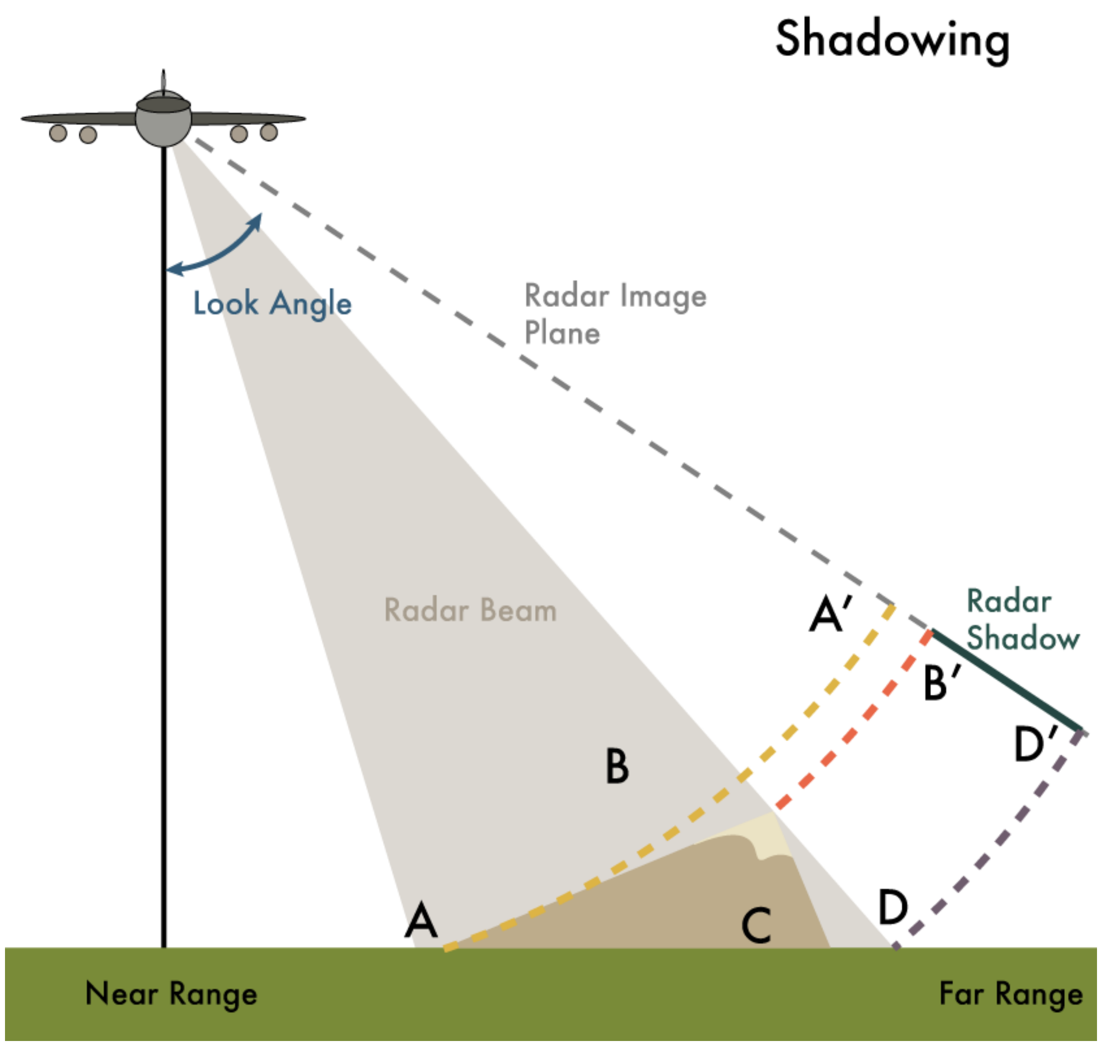
Before Correction



After Correction



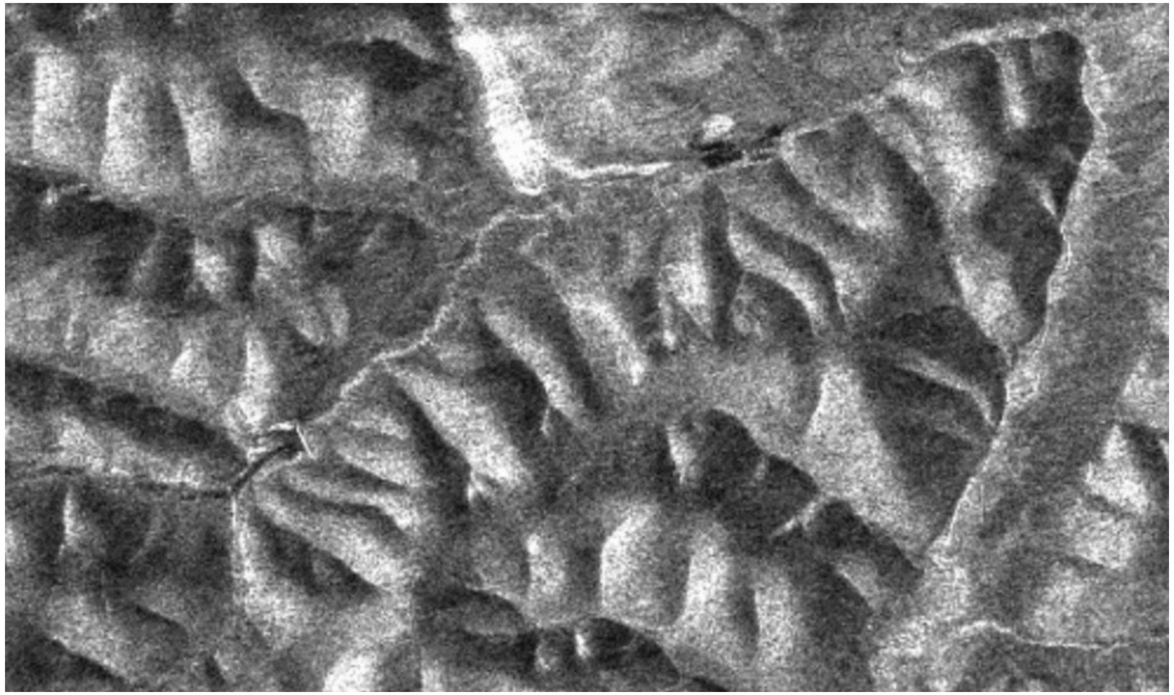
Shadow


Shadowing
Look Angle
Radar Image
Plane
Radar Beam
A′
Radar
Shadow
B′
D′
B
A
C
D
Near Range
Far Range

Radiometric Distortion

- The user must correct for the influence of topography on backscatter
- This correction eliminates high values in areas of complex topography

Before Correction



After Correction

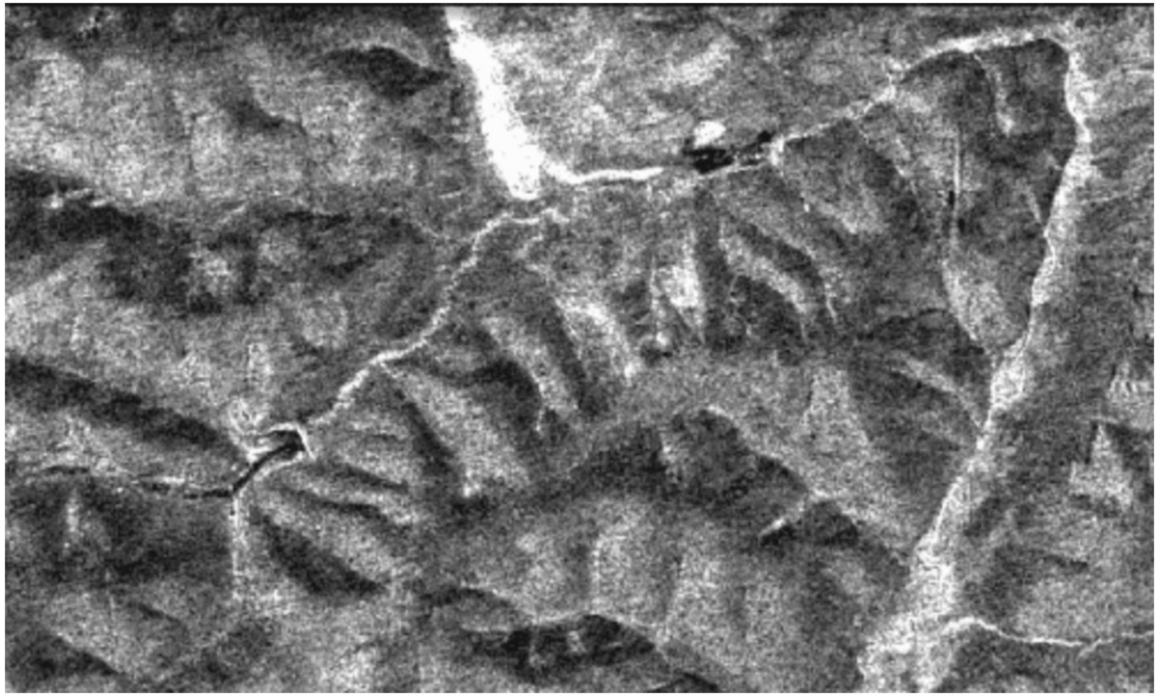
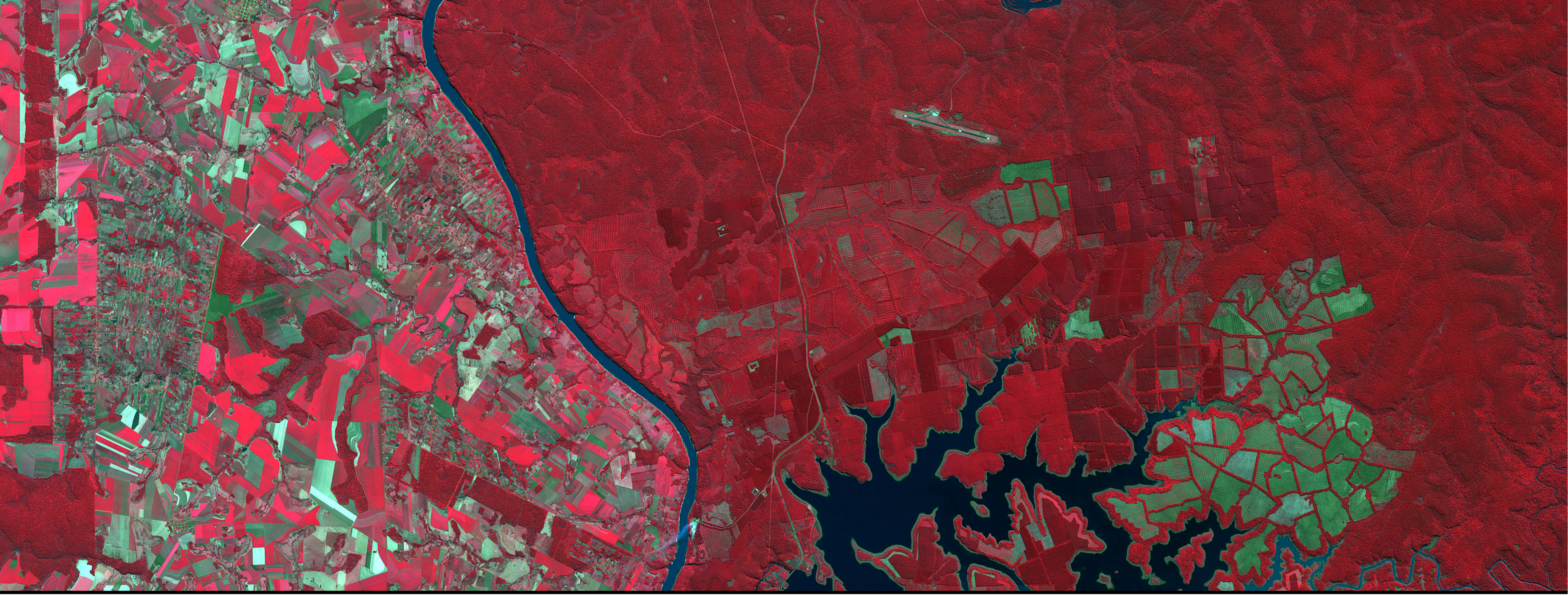


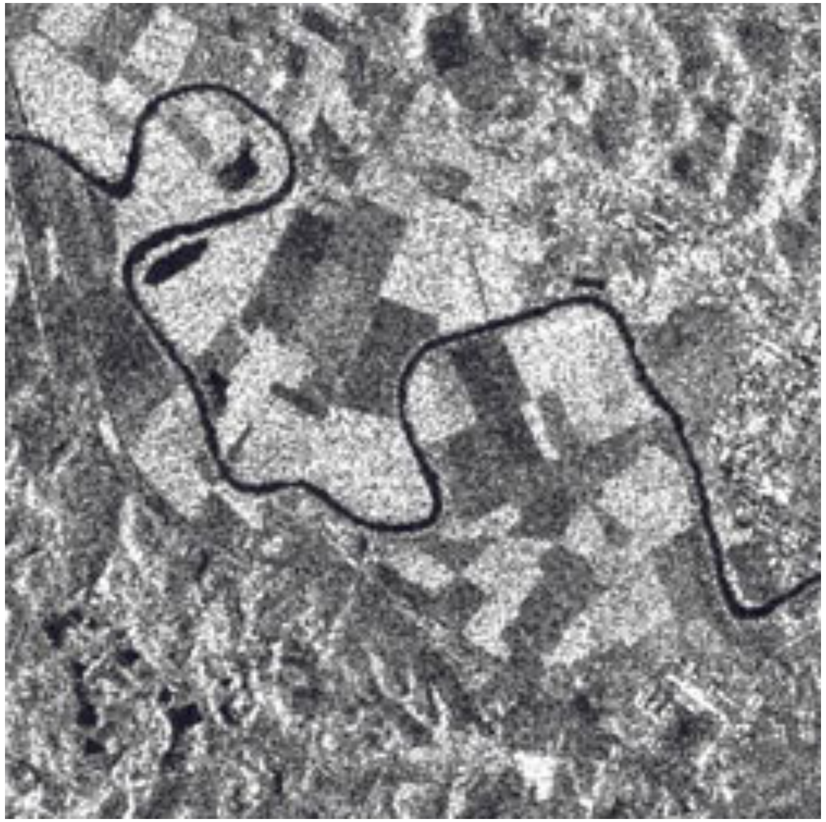
Image Credits: ASF



Speckle

Speckle

Speckle is a granular 'noise' that inherently exists in and degrades the quality of SAR images



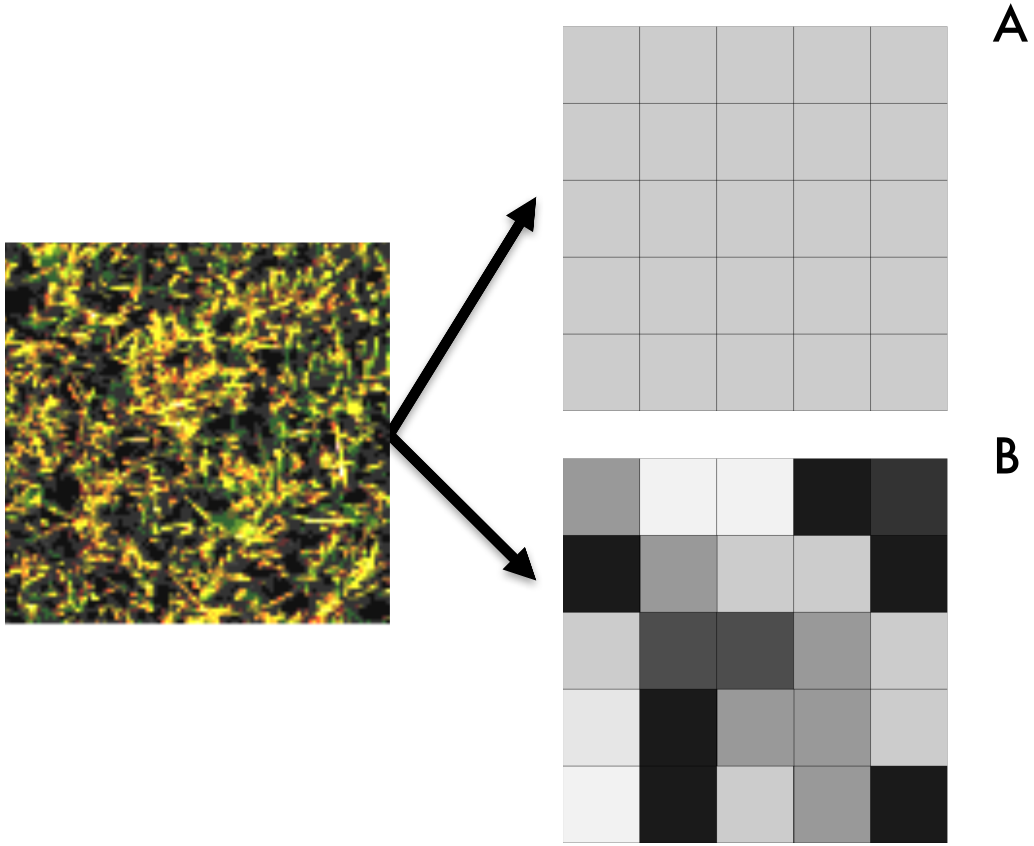
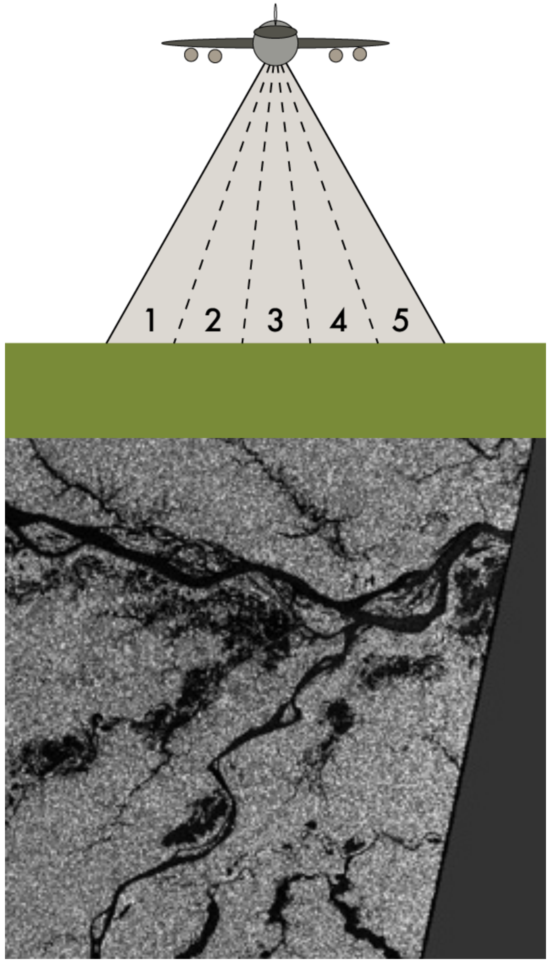


Image Credits: (Left) ESA, Right (Based on an image from Natural Resources Canada)

Speckle Reduction: Multi-Look Processing

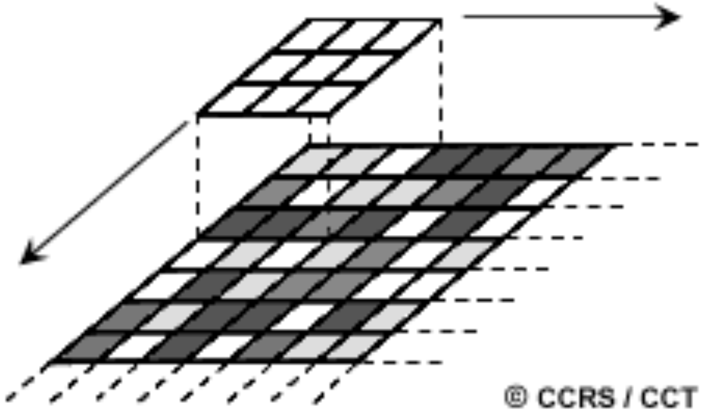
- Divides radar beam into several, narrower sub-beams – e.g. 5 beams on the right
- Each sub-beam is a “look” at the scene
- These “looks” are subject to speckle
- By summing and averaging the different “looks” together, the amount of speckle will be reduced in the final output image

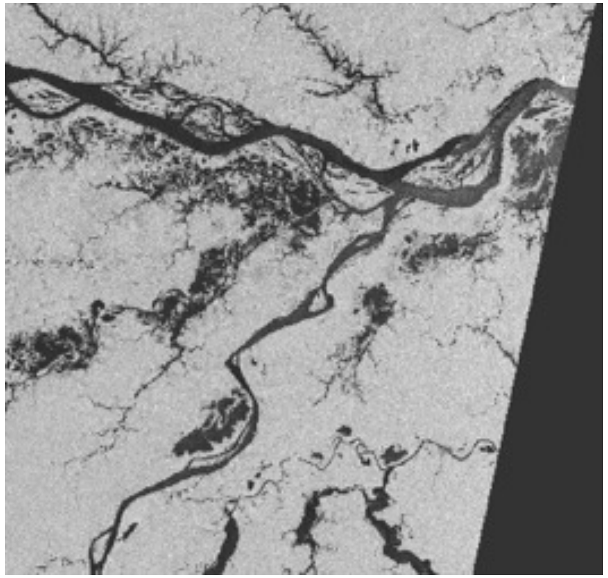


Source: Natural Resources Canada

Speckle Reduction: Spatial Filtering

- Moving window over each pixel in the image
- Applies a mathematical calculation on the pixel values within the window
- The central pixel is replaced with the new value
- The window is moved along the x and y dimensions one pixel at a time
- Reduces visual appearance of speckle and applies a smoothing effect





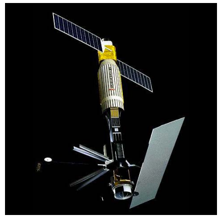
Source: Natural Resources Canada

Radar Data from Different Satellites

freely accessible

freely accessible & reliably repeated acquisition plan

The Legacy:

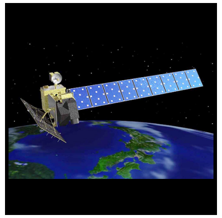
1978

SeaSAT

1991-2011

ERS 1/2

2002-2012

ENVISAT

2002-2012

ALOS-1

1995-2013

Radarsat-1

The New:

2007

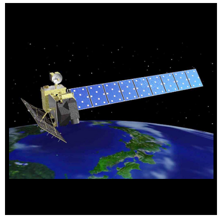
TanDEM-X

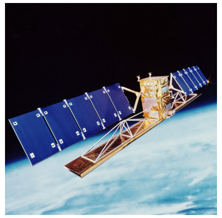
2007

Radarsat-2

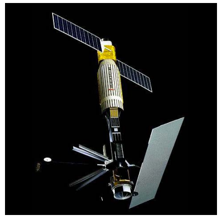
2007

COSMO-SkyMed

2014

ALOS-2

2014

Sentinel-1

The Future:

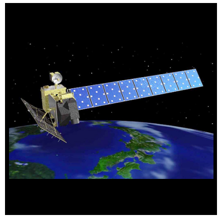
2018

SAOCOM

2018

PAZ SAR

2018

RCM

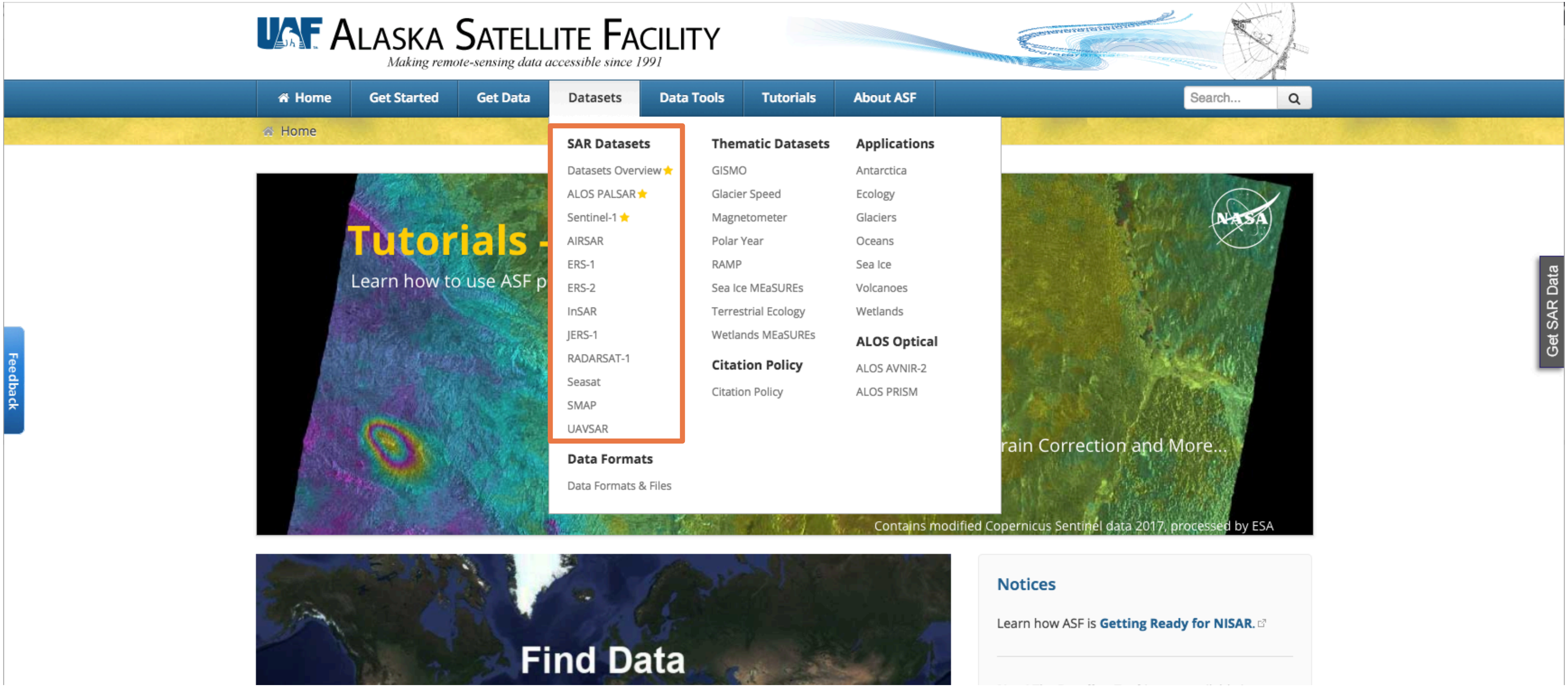
2021

NISAR

2021

Biomass

Credit: Franz Meyer, University of Alaska, Fairbanks

SAR Sources at the Alaska Satellite Facility



NASA-ISRO SAR Mission (NISAR)

- High spatial resolution with frequent revisit time
- Earliest baseline launch date: 2021
- Dual frequency L- and S-band SAR
  - L-band SAR from NASA and S-band SAR from ISRO
- 3 years science operations (5+ years consumables)
- All science data will be made available free and open

NISAR Characteristic:	Would Enable:
L-band (24 cm wavelength)	Low temporal decorrelation and foliage penetration
S-band (12 cm wavelength)	Sensitivity to light vegetation
SweepSAR technique with Imaging Swath >240 km	Global data collection
Polarimetry (Single/Dual/Quad)	Surface characterization and biomass estimation
12-day exact repeat	Rapid Sampling
3-10 meters mode-dependent SAR resolution	Small-scale observations
3 years since operations (5 years consumables)	Time-series analysis
Pointing control < 273 arcseconds	Deformation interferometry
Orbit control < 500 meters	Deformation interferometry
>30% observation duty cycle	Complete land/ice coverage
Left/Right pointing capability	Polar coverage, North and South
Noise Equivalent Sigma Zero ≤ -23 db	Surface characterization of smooth surfaces

Slide Courtesy of Paul Rosen (JPL)

NISAR Hydrology & Subsurface Reservoir Applications

Flood Response

Specific Applications	NISAR Data Product (L1 or L2)	Needed Information Product*
Direction of Inundation	• Geocoded and calibrated product • Geocoded/calibrated SLC would be ok • InSAR coherence and repeat pass coregisted imagery	• Change in open water extent • Flooded forest inundation extent
Change in Water Level in Forested and Urban Areas	InSAR phase and coherence	Measure change in water level in areas where forests and urban areas are inundated
Hurricane & Typhoon Inundation (precipitation and storm surge)	Geocoded coherence map	Aerial map of inundation
Flooding from Runoff and Snowmelt	Geocoded coherence map	Aerial map of inundation

NISAR Hydrology & Subsurface Reservoir Applications

Surface Deformation from Volumetric Changes in Subsurface Reservoirs

Specific Applications	NISAR Data Product (L1 or L2)	Needed Information Product*
Aquifer Drawdown and Recharge (both natural and anthropogenic)	• Geocoded unwrapped interferograms • Geocoded coherence maps • Geocoded LOS vector maps	Rates and time series of vertical surface displacement
Oil and Natural Gas Extraction from Onshore Fields		Rates of vertical surface displacement
Extent and Degree of Mine Collapse	• Raw SAR data (rapid response) • Geocoded unwrapped interferograms • Geocoded coherence maps • Geocoded LOS vector maps	Vertical surface displacement for the time period bracketing the event

NISAR Hydrology & Subsurface Reservoir Applications

Specific Applications	NISAR Data Product (L1 or L2)	Needed Information Product*
	Gas & Fluid Reservoirs	
CO_2 Sequestration	SLC InSAR	Time series deformation
Underground Gas Storage (UGS)	SLC InSAR	• Time series deformation • Deformation from leaks
	Fluid Withdrawal & Injection	
Aquifer Production Triggered Earthquakes	SLC InSAR	• Time series deformation • Deformation from leaks
	Snow Water Equivalent	
Estimate Snow Water Equivalent by Groundwater Basin	• Geocoded and calibrated product • InSAR and PolSAR	• Snow water equivalent

Questions

1. What are the two surface parameters radar is sensitive to?
2. What are the three main backscattering mechanisms?
3. What type of distortions do radar images have?
4. What are the geometric distortions?
5. What type of products can you generate from radar images?
6. How can you use radar images for your specific application?